

**THE GEOLOGICAL RESERVOIR CHARACTERIZATION OF A  
CALCITE-CEMENTED, HETEROLITHIC SHOREFACE RESERVOIR,  
BEN NEVIS FORMATION, HEBRON ASSET**

by

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## **ABSTRACT**

Depositional and diagenetic heterogeneities control reservoir quality and performance and a better understanding of their distribution and impacts on fluid flow will improve reservoir development planning and maximize hydrocarbon recovery. Shoreface deposits within the Ben Nevis Formation at the Hebron Asset consist of alternating beds of facies with contrasting reservoir quality that are diagenetically overprinted with the precipitation of calcite cement. Lower quality fairweather facies are interbedded with higher quality sandstone beds that record periodic pulses of sediment into a quiescent shoreface environment by storm activity. The heterolithic nature of the reservoir and diagenetic alterations caused by calcite cement have implications on reservoir continuity and the spatial distribution of reservoir properties that control fluid behaviour. It is difficult to understand and quantify this distribution from subsurface data alone, and outcrop analogue studies aid in reservoir characterization and modelling by revealing information at the interwell-scale about facies architecture, continuity and distribution. An outcrop study of cemented shoreface parasequences in the Book Cliffs, Utah quantified the dimensions and distributions of calcite concretions and calculated variograms with a horizontal:vertical anisotropy ratio of 5:1. This ratio was used in the stochastic population of facies in the Hebron reservoir model to calculate horizontal variograms from vertical variograms that are well-defined from well log data. Streamline simulation demonstrates the importance that a geologically-realistic representation of cementation has on reservoir performance. Streamlines indicate that concretions act as baffles, making flow paths more tortuous and causing earlier breakthrough.

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### **Statement of Co-Authorship**

I declare that this thesis incorporates material that is a result of joint research under the supervision of professor Dr. Duncan McIlroy. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation, and presentation and discussion of results were performed by the author, and contribution was primarily through the provision of guidance and technical expertise.

# **1 Introduction and Overview**

## **1.1 INTRODUCTION**

Shoreface sediments within the Hebron Asset, offshore Newfoundland (Figure 1-1), contain significant hydrocarbon volumes. An understanding of the inherent heterogeneities of shoreface reservoirs is fundamental to reservoir development planning. Depositional and diagenetic processes create lithologic and petrophysical heterogeneities in sedimentary rocks that affect reservoir fluid flow. The spatial distribution of porosity and permeability is controlled by facies distribution and alterations that occur during diagenesis. Heterolithic interbeds of facies with differing degrees of reservoir quality and diagenetic overprints, such as precipitated calcite cement, create a variable distribution of rock properties. Geologic variations can have significant implications to fluid flow behaviour, creating baffles or barriers to flow, therefore dictating flow pathways through the reservoir. Optimal field development requires accurate reservoir characterization and an improved understanding of reservoir heterogeneities to successfully model fluid flow, in order to maximize hydrocarbon recovery.

Reservoir performance is strongly influenced by depositional and diagenetic heterogeneities that control both reservoir quality and the flow behaviour of hydrocarbons and displacing fluids. The inter-bedded nature of shoreface deposits leads to a juxtaposition of good and poor reservoir quality facies, limiting the spatial

continuity of reservoir properties. The precipitation of calcite cement during diagenesis greatly degrades the reservoir quality of the depositional facies, reducing the porosity and permeability of the host rock (Cant and Ethier, 1984; Amthor and Okkerman, 1998; and Dutton, 2008). The presence of diagenetic cement can alter the flow paths of the reservoir, as tightly cemented concretions form obstacles to flow within the less cemented reservoir facies (Willis and White, 2000; Dutton *et al.*, 2002; and White *et al.*, 2003). The distribution of rock heterogeneity is a key factor in controlling fluid flow and necessitates an understanding of the facies architecture and distribution of permeability pathways and baffles (Begg *et al.*, 1992; Flint and Bryant, 1993; Rosvoll *et al.*, 1997; and White *et al.*, 2004). Permeability contrasts between facies have a marked impact on flow paths and strongly influence productivity and recovery efficiency (Thomas and Bibby, 1991; Corbett *et al.*, 1992; Ciammetti *et al.*, 1995; and Larue and Legarre, 2004).

Reservoir models that quantify the spatial variability of reservoir properties are instrumental in predicting the effects of heterogeneity on reservoir performance during production (Sweet *et al.*, 1996 and Pranter *et al.*, 2005). Proper management of hydrocarbon reservoirs requires an accurate description of the geometry and distribution of geologic variations within reservoir models (Bryant and Flint, 1993). Models that properly forecast fluid flow behaviour must quantify reservoir architecture and identify flow paths that are established in zones containing

significant permeability that occur between facies with contrasting reservoir properties.

The facies model is the foundation for modelling reservoir heterogeneity and dictates the distribution of rock and reservoir flow properties in the reservoir model (Pelgrain de Lestang *et al.*, 2002). Lithofacies are classified in core on the basis of sedimentology and ichnology and interpreted in terms of depositional processes and environments. Using petrophysical log analysis, the identified lithofacies are subsequently grouped into facies types with similar transport properties for modelling. A conceptual depositional model that may be based on sequence stratigraphic and sedimentological concepts, modern and outcrop analogues, and diagenetic processes describes the architecture and spatial distribution of facies in the reservoir. The lateral facies extent is based on the depositional model and determines reservoir continuity. Since petrophysical properties are assigned by facies both the reservoir heterogeneity and fluid flow are therefore governed by characteristics of the facies model. This emphasizes the need to conceptualize a depositional model that best describes the geometry and distribution of facies within reservoir models to accurately predict reservoir heterogeneity and its affect on fluid flow.

In the subsurface, core and petrophysical log data are used to assign facies at discrete well locations that are commonly widely spaced through the reservoir. Well data allows for the classification of lithofacies and demonstrates the level of heterogeneity that exists within flow units in the reservoir. Due to the low density of well data, it is

difficult to define the spatial variability of rock properties from well to well using subsurface data alone. The ability to quantify and model interwell-scale heterogeneity is enhanced by outcrop analogue studies that provide insight into the distribution of geologic variations within equivalent lithofacies and reservoir flow units that cannot be observed in the subsurface (Ravene and Beucher, 1988; Eisenberg *et al.*, 1992; Bryant and Flint, 1993; Kerans *et al.*, 1994; Dutton *et al.*, 2002; White *et al.*, 2004; and Brandsæter *et al.*, 2005).

Outcrops with continuous exposure can demonstrate the degree of facies continuity present within reservoirs and reveal information about facies architecture to fill the inter-well gaps in field data. Outcrop analogues provide both an understanding and quantification of facies dimensions, orientations, and distributions to construct reservoir models that can better predict reservoir heterogeneity and its impact on productivity and the recovery of hydrocarbons (Ciammetti *et al.*, 1995; Willis and White, 2000; Dalrymple, 2001; Dutton *et al.*, 2002; and White *et al.*, 2003). While calcite concretions have been mapped in outcrop and assessed in reservoir simulation studies to demonstrate the effects that these macroscopic heterogeneities have on fluid flow, they have only been well documented in deltaic and deep-marine reservoirs (Dutton *et al.*, 2000; Willis and White, 2000; Dutton *et al.*, 2002; Dutton, 2008). There is, therefore, a gap in the knowledge base that must be filled in order to effectively model shoreface reservoirs.



Calcite concretions affect reservoir fluid flow and are evident in cores and petrophysical logs. While their vertical distribution can be determined from well data, calcite concretions, in particular, are difficult to characterize solely by widely spaced subsurface data. Well spacing is at a much larger scale than the lateral dimensions of these diagenetic features, making it difficult to quantify their lateral extent and distribution. The importance of incorporating calcite concretions into reservoir models is demonstrated by simulation studies based on calcite-cemented outcrop data. Outcrop analogue models show that calcite concretions reduce the upscaled permeability of the reservoir, alter flow paths and displacement fronts, and modify sweep efficiency (White and Willis, 2000 and Dutton *et al.*, 2002).

## **1.2 PURPOSE OF STUDY**

The purpose of this study is to generate a reservoir model for the Ben Nevis Formation (Figure 1-2) at the Hebron Asset that is a realistic representation of the geologic system and its inherent heterogeneity. Using core, well log, and outcrop analogue data, this thesis will aim to characterize and predict the occurrence of heterolithic and calcite-cemented facies within the Ben Nevis Formation. For optimal development planning, it is critical to understand the controls on reservoir quality and to predict the distribution and impacts of low-permeability heterogeneities. Integrating the data into a 3D reservoir model will quantify and predict the impacts that heterogeneities have on fluid flow.

The study objectives are as follows:

1. *Core Description*

Six wells from the Hebron Asset contain core through the Ben Nevis Formation and will be logged and described with respect to grain size, sedimentary structures, bioturbation, calcite-cementation, facies, and stratigraphic surfaces.

2. *Construction of a Depositional and Stratigraphic Model for the Ben Nevis Formation*

Core data will be used to reconstruct a paleoenvironmental depositional model for the Ben Nevis Formation. Facies and stratigraphic surfaces, in combination with petrophysical log data, are used to make correlations across the fields and to create a stratigraphic model for use in predicting distal facies expressions.

3. *Mapping of Calcite-Cemented Zones in an Outcrop Analogue*

Calcite-cemented zones will be mapped in two field locations in the Book Cliffs, Utah (Figure 1-3) and will be described with respect to stratigraphic occurrence and architecture. Field notes, sketches, logs, and photomosaics will be used to determine the size, geometry, and distribution of calcite-cemented zones. It will also be used to determine whether sedimentological parameters constrain the distribution of calcite cementation in shoreface facies. The data are used in the construction of a reservoir model to perform

geostatistical analysis for application in the modelling of the Ben Nevis Formation, a reservoir analogue.

#### 4. *Construction of a Reservoir Model of the Ben Nevis Formation*

A reservoir model of the Ben Nevis Formation will be constructed and streamline simulations will be conducted to assess the impact of calcite concretions on fluid flow. The reservoir model will rely on the conceptual depositional model and incorporate seismic surfaces, petrophysical log data, sedimentological and stratigraphic data from core and well data, facies elements, and outcrop analogue datasets for calcite concretions.

### **1.3 CALCITE CEMENTATION**

Clastic reservoirs are commonly modified by heterogeneously distributed diagenetic cements in the form of discrete concretionary bodies. Such concretions accentuate the heterogeneous reservoir patterns created by variations in depositional parameters and distribution of sedimentary facies. Reservoir quality and performance are strongly controlled by the deleterious effects of calcite cement on porosity and permeability, which impact the volumes, flow, and recovery of hydrocarbons (Cant and Ethier, 1984; McBride, 1989; Molenaar, 1990; Amthor and Okkerman, 1998; Morad, 1988; Willis and White, 2000; Dutton *et al.*, 2002; White *et al.*, 2003; and Dutton, 2008). Calcite concretions inhibit hydrocarbon recovery by acting as low permeability baffles that accelerate breakthrough and reduce sweep efficiency (Willis

and White, 2000; Dutton *et al.* 2002; and White *et al.*, 2003) and predicting their distribution is important for the design and implementation of hydrocarbon recovery strategies.

Cementation is a complex process that is controlled by a number of interrelated factors such as depositional facies, detrital composition, rate of deposition, climate, and burial history of the basin (Morad *et al.*, 2000). Particularly in shallow marine environments, reservoir distribution and diagenetic alterations are strongly controlled by changes in relative sealevel (Morad *et al.*, 2000 and Proust *et al.*, 2001). An understanding of the depositional environmental and sequence stratigraphic controls on diagenesis enhances reservoir characterization and allows for a better prediction of the abundance and distribution of calcite cement.

Within shallow marine sandstones, calcite cement is normally derived from internal sources of dissolved calcium carbonate. The dissolution of biogenic carbonates (allochems) by percolating meteoric waters provides the most significant amount of calcium carbonate and is the dominant source for eogenetic calcite cement in shallow marine and deep-water reservoirs (Bjørkum and Walderhaug, 1990; Morad, 1998; Walderhaug and Bjørkum, 1998; Dutton *et al.*, 2000; and Dutton, 2008). Hence, calcite cementation is most extensive in reservoirs that contain abundant bioclastic constituents and its distribution is strongly linked to depositional facies. Within shallow marine deposits, storm event beds commonly contain eodiagenetic

heterogeneities. This is due to the tendency of storm deposits to have high concentrations of carbonate allochems due to reworking of the seafloor by wave activity (Kantorowicz *et al.*, 1987 and Walderhaug and Bjørkum, 1998).

Eodiagenesis of shallow-marine sandstones results from local diffusional redistribution of calcium carbonate, whereby the biogenetic carbonates act as both the source and nucleation point for the precipitation of calcite cement (Walderhaug and Bjørkum, 1998). As the calcite crystal nucleates, the surrounding biogenic carbonate dissolves and diffuses towards the nucleus, as it is more soluble than the calcite cement. Once it reaches the nucleus, it precipitates as calcite cement, filling the pore spaces of the host sandstone. Calcite continues to precipitate until either all carbonate is dissolved from the surrounding pore waters, or the precipitating cement fills all the available pore space. The distribution of calcite-cemented zones in the reservoir is, therefore, dependent on the original distribution of biogenic carbonate (Walderhaug and Bjørkum, 1998).

Calcite cement commonly occurs as concretions that preferentially form in sandstones that are rich in biogenic debris and their geometries are controlled by the nucleation and calcite crystal growth process (Walderhaug and Bjørkum, 1998). If the biogenic carbonate is concentrated in layers, then the concretions will tend to precipitate and align along layers. However, if the biogenic carbonate is scattered throughout the succession, then the calcite-cemented zones will be more randomly

distributed. If there is a large supply of biogenic carbonate, laterally extensive layers of calcite cement may form as numerous concretions grow and merge into one continuous horizon.

Studies of calcite cement in shallow-marine and deep-water sandstones show that the abundance and distribution of calcite cement is controlled by changes in relative sea level and linked to sequence stratigraphic surfaces (Morad *et al.*, 2000; Dutton *et al.*, 2002; Ketzer *et al.*, 2002; Al-Ramadan *et al.*, 2005; Dutton, 2008; and El-ghali *et al.*, 2008). In shallow-marine reservoirs, calcite cementation is most commonly observed in sandstones that are deposited during the transgressive systems tract (TST) and early highstand systems tract (HST), particularly below parasequence boundaries (PB), the transgressive surface (TS), and the maximum flooding surface (MFS). These surfaces are great candidates for eodiagenetic alteration, because they are frequently marked by bioclastic lags deposits that provide both nucleation points and an ionic source for cementation (Morad *et al.*, 2000; Ketzer *et al.*, 2002; Dutton *et al.*, 2004; and Al-Ramadan *et al.*, 2005).

Cementation along sequence stratigraphic surfaces and in TST deposits, in general, is further enhanced by an increase in bioturbation and organic matter and prolonged residence time of sediments below the seafloor due to low sedimentation rates (Morad *et al.*, 2010). The carbonate content in pore water is locally increased in bioturbated sediments by the bacterial decay of organic matter and results in the nucleation of calcite cement that is further sourced by ionic diffusion from the

overlying seawater (Wilkinson, 1991; Al-Ramadan *et al.*, 2005; and El-ghali *et al.*, 2008).

Diagenetic alterations in clastic sediments may be predicted within a sequence stratigraphic context and strongly linked to the environment of deposition. High rates of relative sea level rise promote eodiagenesis within TST and early HST shallow marine deposits as low sedimentation rates control factors that influence cementation, such as bioturbation (McIlroy *et al.*, 2003) and prolonged residence time of sediments on the seafloor (Macquaker and Taylor, 1996).

Within TST and early HST sandstone deposits, cementation may be extensive along PBs, TSs and MFSs, owing to an abundance of bioclastic shell content within re-worked lag deposits and low sedimentation rates. The distribution of concretions reflects the concentration of biogenic carbonate and is greatest along these surfaces, which may potentially act as baffles to fluid flow. Changes in relative sealevel significantly control the distribution of both depositional and diagenetic reservoir heterogeneities and may be related to systems tracts and sequence-stratigraphic surfaces. The integration of sequence stratigraphy and diagenesis therefore allows better prediction of the controls on reservoir quality and heterogeneity.

#### **1.4 RESERVOIR MODELLING**

Development planning of petroleum reservoirs requires an accurate prediction of the production performance of often, heterogeneously complex reservoirs and relies on a

reservoir model that is representative of the producing system. Reservoir simulation is used to develop and evaluate hydrocarbon recovery strategies and benefits from robust reservoir models that integrate geologic and petrophysical models, to quantify both geologic elements and fluid flow properties. Improved reservoir models integrate structural, stratigraphic, sedimentological (depositional and diagenetic), petrophysical, and reservoir engineering components and employ stochastic techniques to spatially characterize facies and reservoir properties that are heterogeneously distributed in the subsurface.

Reservoir modelling integrates quantitative and qualitative information in a comprehensive workflow to create a three-dimensional representation of the reservoir architecture and the spatial variation of permeability that is geologically realistic. Subsurface data, including seismic, well, core, and production data, delineate the structural and stratigraphic framework of the reservoir model and is the foundation for reservoir characterization. Geologists enhance the modelling process by incorporating their knowledge of the studied system using sequence stratigraphic concepts, development of conceptual depositional models, and integration of analogue data from similar hydrocarbon fields and outcrops.

Seismic interpretation provides the structural framework for the reservoir model. Interpreted horizons and faults delimit the structural container, within which the 3D cellular grid is created. The structural limits are commonly defined at the top and



base of the reservoir by seismically-interpreted horizons and laterally by large scale structural features, such as faults. Internal zonation of the grid is defined by key surfaces that have been correlated and established through the interpreted stratigraphic framework. In shallow marine reservoirs, parasequence boundaries divide the reservoir into conformable successions of genetically related beds, termed parasequences (Van Wagoner *et al.*, 1988). The parasequences form the stratigraphic framework of the model and represent geological zones that contain minimal variation at the scale of the model.

Reservoir characterization requires that a facies classification scheme be defined on the basis of core descriptions that include observations of grain size distribution, sedimentary structures, bioturbation and diagenetic alterations. The facies are interpreted in the context of depositional processes and sequence stratigraphy to create a conceptual depositional model that describes the facies architecture and spatial distribution and predicts the lateral facies extent throughout the reservoir area. A conceptual depositional model is based on the knowledge of the studied systems tract and integrates interpretations and information gathered from sedimentological studies, facies models, sequence stratigraphy concepts, and analogue studies.

Reservoir characterization is facilitated at discrete well locations by a detailed facies description from acquired well data. Realistic reservoir flow simulations rely upon reservoir models that adequately quantify the spatial variability of reservoir

architecture and introduce facies extensions between well locations. The reservoir characterization workflow is enhanced by the use of stochastic modelling to generate realistic distributions of geologic heterogeneity that are conditioned to well data and supported by geologic concepts and interpretations.

Stochastic modelling employs geostatistical techniques to create probabilistic simulations of spatial heterogeneity that honour well data and its statistical variability. Traditional geostatistical techniques use the semi-variogram—routinely referred to as a variogram—to describe the spatial variability of those reservoir properties that vary with both distance, and direction, and provides a measure of linear continuity (Figure 1-4). Variograms are graphs that show how the variance of a property changes with distance between two sample points and are used to identify the spatial correlation of geologic properties in the modelling process.

Geologic properties have a spatial order that varies with separation distance. The closer two points are, the more likely they are to correlate and have similar properties. The variogram presents geological variability as a function of distance and is characterized by the range and sill (Figure 1-4). The range is defined as the distance at which there is no further correlation of a property between data points. The variogram will increase over a particular length scale (the range), showing that properties become more different as distance increases, until the change in variance reaches the variance of the data (the sill). The sill is the upper limit of the variogram

and occurs where the variance of the data reaches a plateau. The range has a significant impact on stochastic modelling as it determines the degree of heterogeneity that will be generated in the simulated realizations. The range is a representation of spatial continuity, where larger ranges produce smoother property distributions and smaller ranges generate more heterogeneously distributed models.

Typically, wells are widely spaced in subsurface reservoirs and the quantity of well data is limited laterally, making it difficult to obtain representative horizontal variograms that characterize the lateral degree of heterogeneity exhibited by geological elements. Geological knowledge of the studied system and additional information, such as that from analogues, augment the horizontal reservoir data in characterizing the spatial structure of the data. Outcrop analogues provide abundant data with regards to horizontal spatial statistics that may be added to the geostatistical database to supplement well data in the analysis of horizontal variograms. The data collected from outcrops can improve the understanding of the variability ranges of properties in reservoirs that is suggested from sparse well data.

Stochastic simulations of equally probable facies distributions are driven by the calculated spatial correlation functions and follow defined sedimentological trends (Srivastava, 1994 and Deutsch, 2002). The stochastically populated facies model honours both the well data and input statistics and is a heterogeneous representation of the known depositional system. Facies are defined in core studies and

characterized by petrophysical well logs into rock types that display different characteristics and flow properties, closely linking the facies and petrophysical models. Facies are modelled separately and independently to ensure that stationarity is retained through the modelling process (Deutsch and Journel, 1998). Stochastic models rely on the assumption of stationarity that the statistical properties remain constant throughout the modelled domain. The defined facies scheme ensures that rock types are separated by their stationarity behaviour, such that each has a constant mean, variance or covariance.

In siliciclastic reservoirs, reservoir properties are correlated to facies and the facies model is critical for reservoir characterization and evaluation. The facies model is populated with petrophysical properties using facies-specific correlations and geostatistical techniques that honour well data and calculated spatial variability. Rock and flow properties are assigned by facies and the distribution of petrophysical properties and flow paths are governed by the heterogeneity established within the facies distribution, highlighting the importance of creating a robust and heterogeneous facies model for more predictive flow simulation.

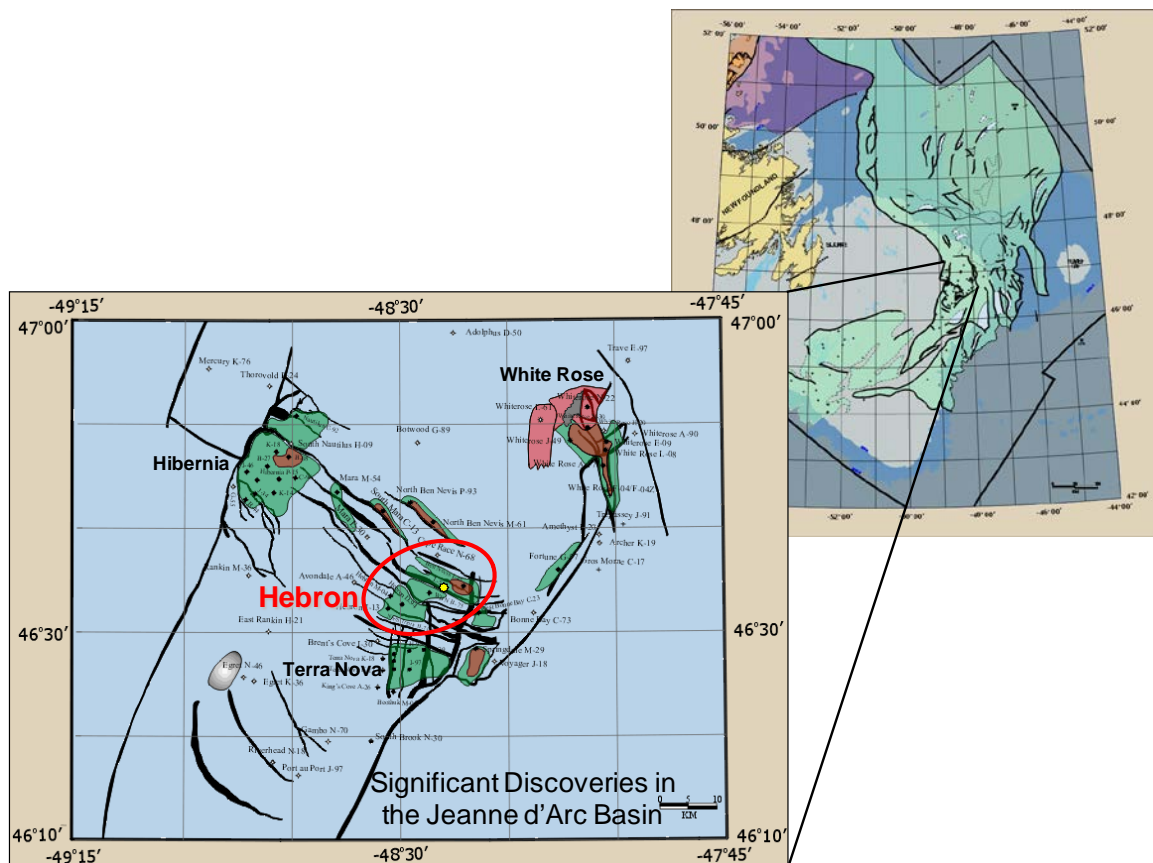
## **1.5 SIGNIFICANCE OF THIS STUDY**

This research assists in providing a better understanding of reservoir heterogeneity and the distribution of facies and diagenetic calcite cement in shoreface reservoirs. Wave-dominated, shoreface deposits comprise a major reservoir type, both in the

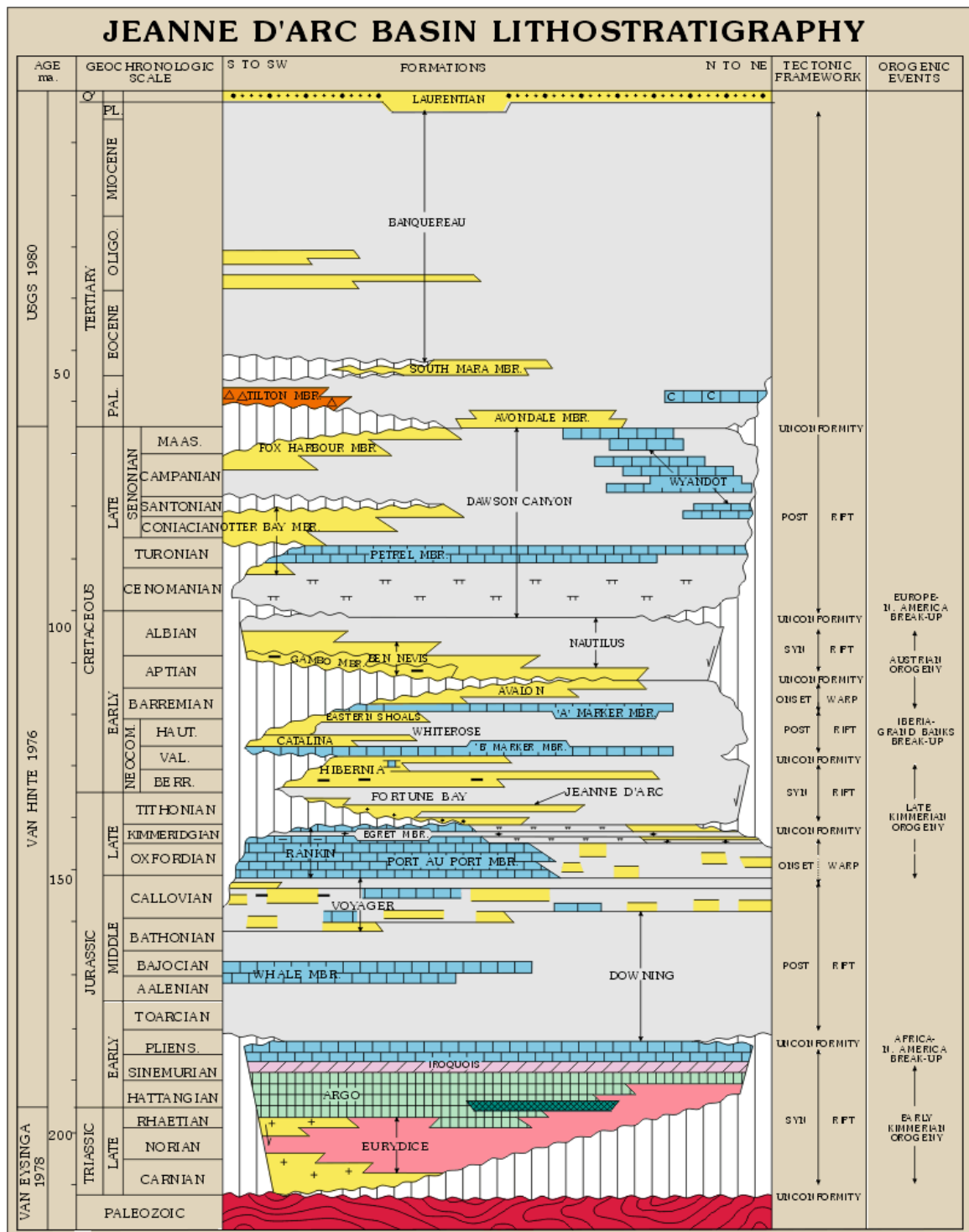
Jeanne d'Arc basin, offshore Newfoundland and numerous basins worldwide. Examples include the Brent Group reservoirs in the North Sea (Husmo *et al.*, 2003), reservoirs in the Niger Delta province, offshore Nigeria (Cook *et al.*, 1999 and Larue and Legarre, 2004) and the Ben Nevis Formation, in the Jeanne d'Arc Basin. Calcite cements are a common diagenetic feature in shoreface reservoirs and its distribution is controlled by depositional environment and the local diffusional redistribution of biogenic carbonate shell material (Walderhaug and Bjørkum, 1998). Developing reservoir characterization models that can identify the controls on calcite cementation in shoreface reservoirs will improve the prediction of flow-related responses and support reservoir development and management decisions.

This study demonstrates how outcrop analogue data can be used in the reservoir modelling process to improve the reservoir characterization of heterogeneous shoreface reservoirs where there is considerable inter-well uncertainty. Calcite concretions, in particular, are difficult to characterize and predict in the subsurface, as well spacing is at a much larger scale than the dimensions of these concretionary bodies. Outcrop analogues provide both qualitative and quantitative information with respect to facies distribution, dimensions, and variation and supplement the sedimentological descriptions and depositional interpretations of subsurface reservoirs used in stochastic modelling.

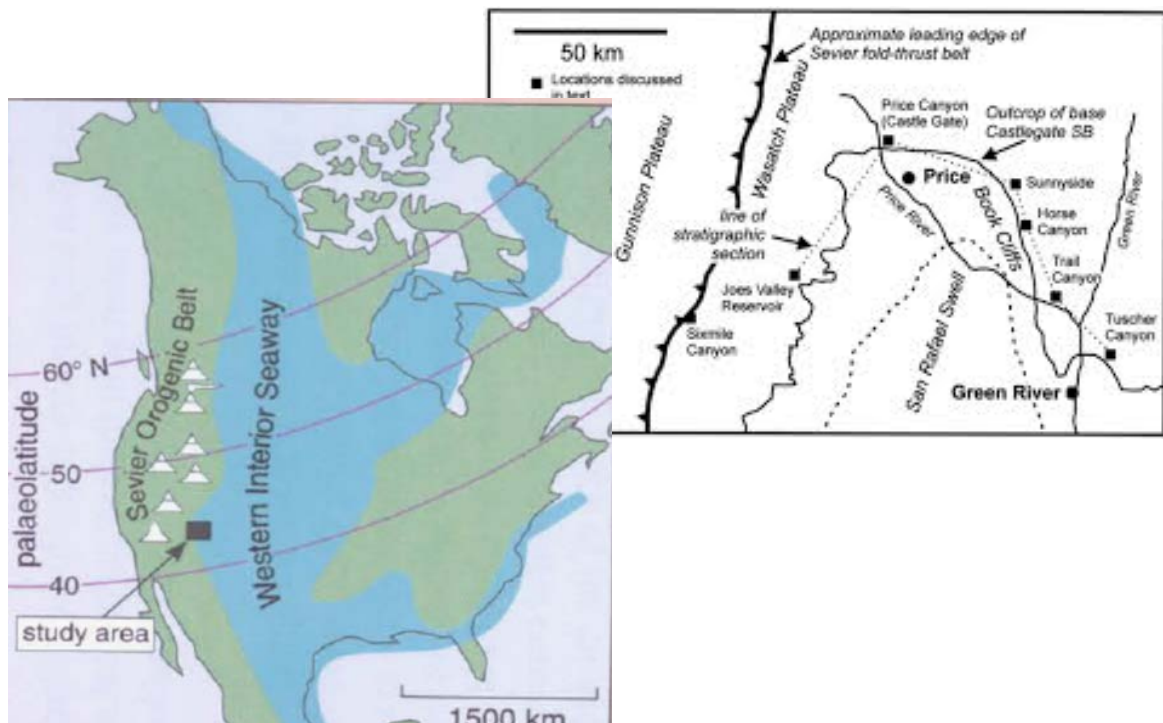
Few studies quantify the geometries and continuity of calcite cement in shallow marine deposits and it is notoriously difficult to provide geostatistical descriptions of these heterogeneities from well data alone. The results of this study will aid in predicting the lateral distribution and dimensions of calcite concretions in shoreface reservoirs and improve the stochastic modelling process by integrating the outcrop observations into geostatistical techniques that quantify spatial variability. Improved modelling efforts will prove to be valuable for understanding the implications of these low permeability features on reservoir flow and performance.



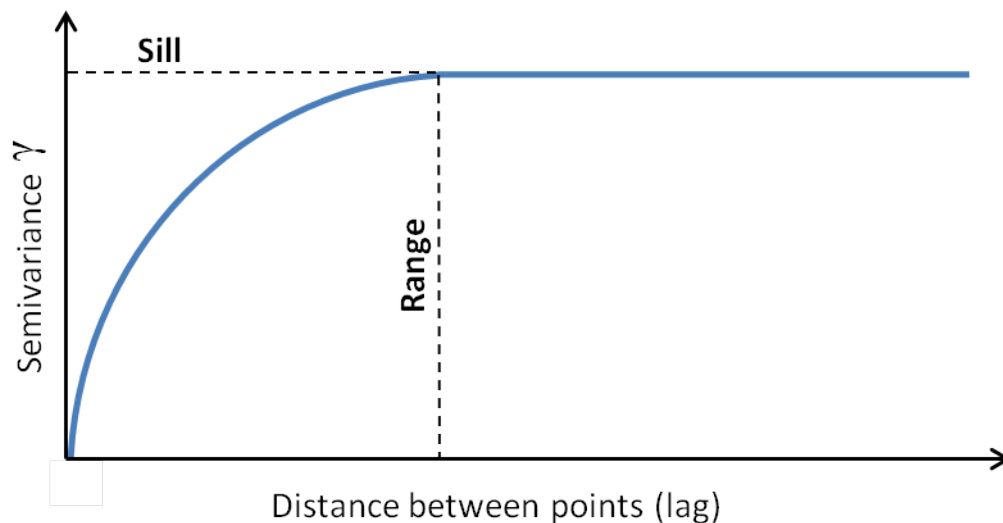
**Figure 1-1.** Location of the Hebron Asset within the Jeanne d'Arc Basin, offshore Newfoundland, Canada and other significant discoveries in the basin.



**Figure 1-2.** Lithostratigraphic chart of the Jeanne d'Arc Basin.



**Figure 1-3.** Location of the Book Cliffs in the Western Interior Basin in Utah (from Howell and Flint, 2003). Field study areas included two outcrops exposed near Price, Utah in Carbonville and Garley Canyon.



**Figure 1-4.** Variograms show how the variance of a property changes with distance between two sample points and are characterized by a sill and a range. The sill is the semivariance value at which the variogram levels off and the range is the lag distance at which the variogram reaches the sill.



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## **2 Sedimentology and Reservoir Quality of the Ben Nevis Formation in the Hebron Asset: A Wave-Dominated Shoreface Succession**

### **2.1 INTRODUCTION**

The Ben Nevis Formation is the most common petroleum reservoir in the Jeanne d'Arc Basin. It is a siliciclastic succession that alternates between poor reservoir quality fairweather deposits and high quality storm deposits. The local preservation of heterolithic, fine-grained deposits between storm-induced deposits that are commonly amalgamated, creates variability within the succession that can potentially influence the flow behavior of the reservoir. The lateral extent of the heterolithic interbeds present risks to reservoir continuity and are possible baffles to fluid flow.

Optimal development of the prolific hydrocarbon-bearing Ben Nevis Formation at the Hebron Asset requires an accurate model of the reservoir distribution. The highly variable nature of the Ben Nevis Formation requires careful study of the relationship between sedimentary facies, ichnology and reservoir characterization at a detailed bed scale. An integrated approach to the prediction of facies-related reservoir properties involves a detailed sedimentological analysis. The objective of this study is to describe the sedimentology of the Ben Nevis Formation at the Hebron Asset in order to interpret the paleoenvironment of deposition. A good understanding of the paleodepositional setting is critical in identifying the distribution and continuity of facies, in order to predict reservoir quality and performance in the study area.

## 2.2 GEOLOGICAL SETTING

Located in the petroleum-rich Jeanne d’Arc Basin, the Hebron Asset consists of the Hebron, West Ben Nevis and Ben Nevis fields. The Hebron Asset is located approximately 340 km east-southeast of St. John’s, NL, on the northeast Grand Banks (Figure 2-1). Classified as a significant discovery, the Hebron Asset was discovered in 1980 and contains an estimated resource of 3176 MMbbls of oil within 3 petroleum reservoirs: the Ben Nevis Formation; the Hibernia Formation; and the Jeanne d’Arc Formation (C-NLOPB, 2012) (Figure 2-2). Six exploration/delineation wells have been drilled within the asset: Mobil *et al.*, Ben Nevis I-45, the discovery well; Chevron *et al.*, Ben Nevis L-55; Petro-Canada *et al.*, West Ben Nevis B-75; Mobil *et al.*, Hebron I-13; Petro-Canada *et al.*, Hebron M-04; Petro-Canada *et al.*, Hebron D-94 and several offset wells exist, including Petro-Canada *et al.*, North Trinity H-71 (Figure 2-3).

The tectonic evolution of the Jeanne d’Arc Basin resulted in the structural development of several significant petroleum reservoirs, including the Hebron Asset and the Hibernia, Terra Nova, and White Rose fields. The Jeanne d’Arc Basin developed in response to three Mesozoic rifting episodes that took place during (1) the late Triassic-early Jurassic periods; (2) the late Jurassic-early Cretaceous periods; and (3) the mid Aptian-late Albian stages of the Cretaceous Period (Hubbard *et al.*, 1985; Enachescu 1987; Tankard and Welsink, 1987; Grant *et al.*, 1988; Tankard *et al.*, 1989; Hiscott *et al.*, 1990; Sinclair, 1988; and Sinclair, 1993). The rifting episodes were related to continental break-up and opening of the North Atlantic Ocean, and were

followed by phases of thermal subsidence. These extensional episodes resulted in the development of a series of half-graben and horst complexes throughout the region. Large and complex structural closures were created by the growth of a set of NW-SE trending to E-W trending normal faults, termed the "trans-basin fault trend" (McAlpine, 1990 and Grant and McAlpine, 1990), during the Aptian-Albian rift episode that interacted with fault sets that developed during the previous rift episodes.

The Hebron Asset is centered upon a series of five northwest-southeast trending fault blocks, delineated during the third rift episode (Figures 2-3 and 2-4). The complex consists of horst and graben blocks and is located near the southeast end of the Ben Nevis fault trend in the Jeanne d'Arc Basin (Figure 2-1). The Hebron Field is comprised of two adjacent fault blocks that are separated by a SW-dipping fault: the relatively un-faulted horst block penetrated by M-04 and D-94; and the downthrown block penetrated by I-13 to the southwest (Figure 2-4). The West Ben Nevis and Ben Nevis fields consist of tilted blocks downthrown to the northeast from the horst block from south to north (Figure 2-4). There also is an undrilled graben block downthrown to the southwest from the Hebron I-13 fault block.

### **2.2.1 Ben Nevis Formation**

The Ben Nevis Formation was deposited during the third rift episode, and consists of mid Aptian to late Albian shallow marine sediments deposited during a period of net transgression (Sinclair, 1993) (Figure 2-2). Active faulting during deposition had an



impact on subsidence rates and sediment supply resulting in thickness variations throughout the basin. Growth faulting within the Ben Nevis Formation is evinced by increased isopach thicknesses across faults. In the Hebron Asset, the Ben Nevis Formation thickens from southwest to northeast, from the Hebron Field to the West Ben Nevis and Ben Nevis fields (Figure 2-4). With this increased thickness, however comes a degradation in reservoir quality as the syn-depositional faulting created increased water depths in the downthrown blocks to the northeast, and therefore deposition of more distal facies.

The Ben Nevis Formation is bound at the base by the mid-Aptian unconformity and is overlain by the marine Nautilus Shale, which acts as the top reservoir seal for this formation (Figure 2-2). The mid-Aptian unconformity is an angular rift-onset unconformity that formed as a result of uplift and erosion due to continental break-up during the third rift phase (Tankard and Welsink, 1987; Tankard *et al.*, 1989; and Sinclair, 1993). As a result of this uplift, the mid to late Aptian is dominated by lowstand to early transgressive system tracts. The Ben Nevis Formation is considered to be an aggradational to retrogradational parasequence set that formed in response to an increase of subsidence rates due to active faulting, in combination with continued uplift. The Ben Nevis Formation shows a net-upward fining and is characterized by stacked parasequences of progradational shoreface sediments that show a strong influence of episodic storm events. The Ben Nevis Formation consists of clean sandstones inter-bedded with bioturbated argillaceous and silty sandstones and contains variable amounts of calcite cement (Harding, 1988; Hiscott *et al.*, 1990;

Sinclair, 1993; Pemberton *et al.*, 2001; and Tonkin *et al.*, 2010). An ichnological study of the Ben Nevis Formation in Ben Nevis L-55 by Tonkin *et al.* (2010) indicates a normal marine trace fossil assemblage dominated by *Ophiomorpha*, *Thalassinoides*, *Asterosoma*, *Phycosiphon* and *Diplocraterion*.

## **2.3 SEDIMENTOLOGY**

451.57 m of core from five wells in the Hebron Asset: I-13; D-94; M-04; B-75 and L-55, and from one offset well, H-71, were examined and logged in detail, as part of an integrated sedimentological and ichnological study (Tonkin *et al.*, 2010) (See Appendices A and B). Based on grain-size, sedimentary structures, and ichnology, six main facies and some diagenetic components were identified in core (Table 2-1 and Figure 2-5) and subsequently used to identify depositional environments of the cored interval (Figures 2-6 and 2-7).

### **2.3.1 Facies**

#### **Facies 1: Bioturbated sandstone with shell debris**

##### *Description*

Facies 1 consists of very fine to fine-grained sandstone with silt. This facies is highly bioturbated and no physical sedimentary structures are observed (Figure 2-5a and b).

Intensity of bioturbation ranges from 60-100%. There is a diverse ichnofaunal assemblage that is dominated by *Ophiomorpha* and also includes *Planolites*, *Teichichnus*, and *Phycosiphon*. Articulated and disarticulated shell fragments are present, where the lower part of the cored interval is dominated by oysters and the upper part is dominated by serpulid worm tubes. Based on the distribution of shell debris, the facies is further subdivided into two subfacies: (1) Subfacies 1a contains a sparse and scattered distribution of shells (Figure 2-5a); and (2) Subfacies 1b contains beds of clast-supported shelly debris (Figure 2-5b). Dispersed carbonaceous debris, including wood fragments, is common in this facies and is often pyritized. Beds are typically less than 1 m in thickness, commonly showing subtle upward-fining of the matrix.

### *Interpretation*

The high levels of bioturbation and paucity of physical sedimentary structures within the upper very fine to fine-grained, silty sandstones reflect deposition within a comparatively low energy hydrodynamic regime. It could be considered the background facies to the system, which in open, shallow marine settings may be punctuated by rapid depositional storm events. The lack of physical sedimentary structures and the presence of intense bioturbation suggest that there were either extended periods of time between storm event bed deposition or very high rates of bioturbation (the former interpretation is preferred herein). It indicates deposition and bioturbation of sediments in an open, shallow marine environment during low energy

conditions, whereby fine-grained sediments settle from suspension and are subsequently reworked by organisms. Facies 1 constitutes fairweather interstorm deposits and due to the high sand content and presence of carbonaceous debris is interpreted to be deposited within a lower shoreface setting. It is representative of the proximal interstorm background sedimentation within the succession and can be modelled as such. Several different ichnofabrics can be recognized within this facies.

The presence of oyster shells may be taken to indicate a lagoonal source for the shell debris transported by ebb-tidal currents into an open marine setting where they are reworked in a wave-dominated setting. The two different patterns of shell debris within beds of this facies are suggested to reflect proximity to the source of shells (inferred to be tidal inlet channels). We propose that subfacies 1a was deposited up-drift of an ebb-tidal channel where there is no local source of oyster shells. In contrast, subfacies 1b is interpreted to be deposited down-drift of an inlet channel, and shells washed from the inlet channel by ebb-tidal currents were redistributed by longshore currents in a down-drift direction (Figure 2-8). The presence of carbonaceous plant debris also suggests that facies 1 was deposited near a distributary channel.

## **Facies 2: Bioclastic sandstone**

### *Description*

Facies 2 consists of bioclastic fine-grained sandstone beds that typically have erosive basal contacts overlain by a lag of clast-supported shell beds that contain abundant bivalves, gastropods and serpulid worm tubes (Figure 2-5c). The shell beds show vertical sorting of shells, based on size, grading from 6-8 cm oyster shells at the base to smaller cm-scale shell fragments, particularly serpulid worm tube fragments, at the top of the bed. These shell rich beds (or more likely bedsets) are up to 3 m thick and are gradationally overlain by low-angle and parallel laminated sandstones of facies 7 (described below) with sparse shelly debris. Bioturbation is rare and there is a low abundance and diversity of trace fossils, of which spreiten-burrows are the dominant ichnofauna.

### *Interpretation*

The basal erosive surface that characterizes this type of bioclastic deposit is overlain by highly winnowed shell debris and indicates that the bioclastic fine-grained sandstone was deposited under high energy conditions. In open, shallow marine settings, periodic storm events provide high pulses of sediment and bioclastics to the system above storm wave base. Facies 2 is interpreted to be a storm event bed with a winnowed shell lag or coquina (cf. Kidwell 199\*). We consider that during intense storms, shells were transported from offshore and deposited landward as coquina shell beds in the proximal lower shoreface. Shell-fragment size distribution suggests current-sorting by waning currents and the dominance of broken shells suggests comparatively

long transport paths. The paucity of syn-depositional trace fossils relative to other associated facies indicates deposition during episodic, high energy hydrodynamic events. This demonstrates that high sedimentation rates lead to the preservation of physical sedimentary structures, as they are not obliterated by bioturbation.

### **Facies 3: Laminated sandstone**

#### *Description*

Facies 3 consists of very fine to fine-grained, laminated sandstone (Figure 2-3d, e and f). Beds are up to 20 cm thick and have sharp, erosional basal contacts. The most common physical sedimentary structures in the sand are parallel to low-angle cross-lamination. However, ripples and ripple-crossbedding may be developed at the top of beds (Figure 2-5g). Clay drapes and carbonaceous laminae are common (Figure 2-5e). Fine-grained debris, including finely comminuted carbonaceous material and small woody fragments, are common and may be either coalified or pyritized. Beds are commonly unbioturbated, but where present, the trace fossil assemblage predominantly includes *Ophiomorpha* with accessory *Chondrites* and *Planolites*. Sideritized mudstone rip-up clasts are commonly present as lag deposits along basal scour contacts (Figure 2-5d). The presence or absence of a basal lag deposit further subdivides facies 3 into two subfacies: (1) Subfacies 3a is characterized by the presence of a basal sideritized mudstone clast lag (Figure 2-3d); and (2) Subfacies 3b contains no basal mudstone lag deposit (Figure 2-3f).

### *Interpretation*

The presence of low-angle cross-lamination, in association with an erosive-based sandstone with basal lag deposits, passing upwards into finer-grained or ripple cross-laminated sandstone suggests that facies 3 was deposited under high-energy, and eventual waning hydrodynamic conditions. Facies 3 is interpreted to represent storm event beds that were deposited above storm wave base along the shoreface profile. While it is difficult to be certain in core material, we consider it likely that the low angle cross-lamination within the sandstone beds is the core-expression of either hummocky and/or swaley cross-stratification (HCS and SCS, respectively), suggesting storm-induced deposition in the lower shoreface and offshore transition zone (Harms *et al.*, 1975). The occurrence of ripples and ripple cross-lamination at the tops of some beds indicate post-storm reworking by waves during fairweather periods and suggest that these storm beds were deposited above fairweather wave base in the lower shoreface. The general lack of syn-depositional trace fossils is again taken to reflect the intense hydrodynamic activity and rapid rates of deposition that characterize the event beds within this depositional system. The low intensity of bioturbation, exclusively from post event-bed colonization, may also be indicative of a high frequency of events, allowing little time for bioturbation to develop before the next storm event.

The observed fine-grained drapes that define the laminae are interpreted to show tidal coupling, where the mud and carbonaceous drapes were deposited from suspension during alternating high and low slack-water periods (Figure 2-5h). We consider that

the presence of tidal couplets toward the tops of the sandstone beds indicates some degree of tidal modulation of storm-generated currents, perhaps close to a distributary mouth or ebb tidal delta. A basal lag deposit of sideritized mudstone clasts mark an increase in energy and indicate that subfacies 3a was deposited in a lower accommodation setting than subfacies 3b. These clasts can be produced in estuaries, tidal flats and other protected back-barrier/lagoonal settings (Macquaker and Taylor, 1996) and their anomalous presence in this facies supports deposition in proximity to a tidal inlet. These storm deposits are the main reservoir rock type in the region.

#### **Facies 4: Inter-bedded sandstone with laminated and bioturbated mudstone**

##### *Description*

Facies 4 consists of very fine to fine-grained sandstone inter-bedded with muddy sandstone (Figure 2-5i). This heterolithic facies is comprised of clean sandstone with sub-parallel laminae overlain by argillaceous sandstone with moderate bioturbation. The boundary between the two lithologies is diffusely bioturbated. This facies is termed “lam-scam” because laminated beds grade into bioturbated beds, where trace fossils have scrambled the laminations (Howard, 1972). The cm-thick sandstone beds are planar to wavy-laminated and have low levels of bioturbation. Trace fossils within the laminated sand beds are dominated by *Ophiomorpha*, with accessory *Chondrites* and *Phycosiphon*. The overlying cm-thick muddy sandstone beds have moderate levels of



bioturbation and are dominated by *Phycosiphon*. Angular, sideritized mud-flake breccias sometimes form a basal lag to this facies.

#### *Interpretation*

The inter-bedded sandstone and muddy sandstones of facies 4 reflect variable sedimentation rates and hydrodynamic energy. The “lam-scram” nature of this heterolithic facies indicates waning flow energy through deposition, probably with extended fairweather conditions and weakly erosive currents during hydrodynamic events. The lower laminated sandstone beds are deposited under moderate energy flow conditions, and as flow wanes, become bioturbated (“scrambled”) due to increased bioturbation by shallow, burrowing benthonic organisms under lower energy conditions. The preservation of laminae in the sandstone beds is considered to reflect moderate energy storm deposition in association with an offshore transition zone setting. The low energy fairweather conditions in this environment promote bioturbation of the fairweather deposits, and possibly post-depositional bioturbation of the preceding storm deposits, as organisms rework the deposited sediments.

### **Facies 5: Bioturbated silty mudstone**

#### *Description*

Facies 5 consists of silty mudstone, inter-laminated with very fine-grained sandstone stringers (Figure 2-5j and k). This facies is intensely bioturbated, and has both the

highest abundance and diversity of trace fossils. *Ophiomorpha* is the dominant ichnotaxon, found in association with *Phycosiphon*, *Teichichnus*, and *Asterosoma*. Rare physical sedimentary structures allow recognition of two subfacies: (1) Subfacies 5a contains lenticular bedding (Figure 2-5j); and (2) Subfacies 5b has no primary sedimentary structures preserved (Figure 2-5k). Facies 5 is more abundant towards the top of the Ben Nevis Formation throughout the Hebron Field in bedsets up to 1 m thick.

#### *Interpretation*

The predominance of mudstone deposition and the intense degree of bioturbation suggests that Facies 5 was deposited under the lowest hydrodynamic energy conditions within the system. The abundance, diversity and types of bioturbation are representative of an open marine trace fossil assemblage in low energy environments, where both vertical and horizontal burrows may be preserved. Laminated mudstone beds were deposited from suspension and subsequently reworked by both suspension and deposit feeders. Facies 5 is thus interpreted to be deposited within the offshore transition zone and represents the distal interstorm background sedimentation within the succession. The interbeds of lenticular-bedded sandstones in Subfacies 5a suggest deposition as a result of weak storm activity that created small-scale wave ripples. The complete destruction of primary sedimentary fabric in Subfacies 5b suggests that the rate of bioturbation was relatively high relative to the rate of sedimentation. The

relative importance of bioturbation rate versus rate of sediment supply is not resolvable, but it is suggested that Subfacies 5b was deposited further distally than Subfacies 5a, where rates of sediment supply are likely to be lower and rates of bioturbation are likely to be relatively high.

### **Facies 6: Bioturbated and laminated mudstone**

#### *Description*

Facies 6 consists of inter-bedded mudstone containing very fine-grained sandstone stringers (Figure 2-51). The occurrence of facies 6 is concentrated in the upper part of the succession. Beds are 2-5 cm thick and commonly overlie facies 2. The mudstone beds are laminated and contain sharp-margined, sand-filled *Thalassinoides* isp. burrows that would be referred by some authors to be the *Glossifungites* ichnofacies.

#### *Interpretation*

The sharply preserved laminae in an offshore shallow marine succession are anomalous, as is the preservation of multiple closely spaced firmgrounds. The possibility of the firmgrounds being concealed firmgrounds that are colonized from much higher in the stratigraphy can not entirely be ruled out. The rapid deposition of mudstone with low organic matter content that is likely to preclude burrowing is consistent however with deposition from a mud-rich hyperpycnal flow (cf. McIlroy,

2004; Macquaker *et al.*, 2010; and Ichaso and Dalrymple, 2010). The mudstone deposits themselves are colloquially termed fluid mud deposits and form as a result of a rapid supply of mud in low energy conditions during post-storm periods.

### **2.3.2 Secondary Diagenetic Components**

The reservoir rock also contains an abundant amount of secondary diagenetic components, such as calcite cement and siderite clasts. Calcite-cemented zones are significant throughout the core and are separated into 2 common groupings: (1) Calcite concentrated within coquina-type shell bed deposits (Figure 2-9a) (Kidwell and Bosence, 1991); and (2) Nodular concretions that have irregular boundaries and rounded edges in core that cross-cut beds (Figure 2-9b). Both types of calcite cementation have scales of approximately 1 cm to several meters in thickness. Although not considered a significant component, mudstone rip-up clasts are commonly sideritized.

## **2.4 FAIRWEATHER AND STORM DEPOSITS**

Wave-dominated shorelines may be characterized by a hydrodynamic regime of contrasting levels, resulting in deposits of a heterolithic nature. Low energy conditions during fairweather periods may be punctuated by episodic storm events, in which there is a rapid supply of sediment to the open marine setting. The six facies described

above were classified as either fairweather or storm deposits and reflect changes in energy within the depositional system and are considered in their paleoenvironmental context below.

Bioturbated interbeds in the aforementioned setting represent fairweather, perhaps summer conditions and are represented in the cored intervals as bioturbated silty sandstones of facies 1 and the more distal expression as bioturbated silty mudstones of facies 5. During the low energy fairweather conditions, sediments are deposited on the seafloor and are reworked by organisms, resulting in fine-grained deposits that are intensely bioturbated. These facies are interpreted to represent slow, continuous deposition and evidence for repeated overprinting can be recognized. There is likely to be an onshore-offshore trend (i.e. perpendicular to the inferred shoreline) in which reservoir quality degrades in a distal direction due to the facies becoming progressively mud-rich and finer-grained. The cored interval is dominated by the fairweather deposits of highly bioturbated, very fine to fine-grained sandstones of facies 1 that are deposited in the lower shoreface. The fairweather bioturbated sandstone deposits grade into the mud-rich siltstones of facies 5 that are deposited in the offshore transition zone and contain the most intense and diverse levels of bioturbation within the cored interval.

Discrete sandstone beds with preserved sedimentary structures may be produced by intense storms in which rates of sedimentation are high, meaning that only deep tier burrows are likely to destroy physical sedimentary structures. They are typically inter-

bedded with the “background” or fairweather deposits of the system and the episodic nature of these beds suggests deposition of sediment and bioclastics during storm events. Storm-induced beds are represented in the cored intervals as facies 2 and 3 and consist of bioclastic and laminated sandstones that are less intensely bioturbated than the fairweather deposits. Bioturbation is suppressed as these deposits are deposited during periods of intense hydrodynamic activity, in which any presence of bioturbation is exclusively post-depositional (cf. Aigner, 1985). The intermittent occurrence of these deposits throughout the cored interval suggests that such storm events are periodic in the succession. However, owing to the extensive open nature of the inferred shoreline, storm-induced deposits are likely to be widespread and laterally continuous in extent as a result of sediment transport by longshore drift, particularly in the down-drift direction of origin (inferred to be tidal inlet channels herein). During transitional post-storm periods, as intense storm-induced conditions return to fairweather conditions, laterally extensive fluid mud layers may be deposited. The fluid mud deposits immediately overlie the storm-generated HCS sandstone beds and are a result of sedimentation from suspension of previously deposited mud.

Variable sedimentation rates as a result of alternating fairweather and storm conditions in a shoreline setting is evident in the “lam-scam” nature of facies 4 within the cored interval. The laminated muddy sandstone beds are interpreted as rapid post-event bed deposits in paleoenvironments with moderate hydrodynamic energy. Laminated beds are deposited under medium flow regime conditions, for example during storm events

in distal environments such as the offshore transition zone, followed by “scrambling” of the sediment by bioturbation during low energy interstorm periods.

There is a diverse assemblage of deposit and suspension-feeding marine trace fossils in the cored interval, suggesting deposition within a shoreface setting that is characterized by varying levels of hydrodynamic energy (Figure 2-10). The observed ichnofauna is dominated by *Ophiomorpha*, and includes *Phycosiphon*, *Thalassinoides*, *Planolites*, *Chondrites*, *Diplocraterion*, *Teichichnus*, *Palaeophycus*, and *Asterosoma*. The intensity of bioturbation reflects relative rates of deposition and bioturbation and suggests that deposition occurred during varying and contrasting hydrodynamic conditions that exist within the zones along the storm-influenced shoreline profile.

Above storm wave base (SWB), deposition is controlled by alternations of low and high energy conditions and presents itself as fairweather and storm deposits. The intensity, diversity and type of bioturbation are facies-controlled and used to interpret the depositional setting (Figure 2-10). Low energy conditions favour bioturbation and there is a transition from suspension-feeding to deposit-feeding organisms in lower energy settings. Fairweather deposits are highly bioturbated as low energy conditions on the seafloor promote infaunal reworking of sediments. Bioturbation intensity in the fairweather deposits varies between 60 and 100%, but is typically about 75%. Fairweather ichnofabric associations include *Ophiomorpha-Phycosiphon* (bioturbated silty sandstones of facies 1 and bioturbated silty mudstones of facies 5), *Ophiomorpha-Asterosoma* (bioturbated silty mudstones of facies 5), *Teichichnus-Phycosiphon*

(bioturbated silty mudstones of facies 5) and burrow mottled (bioturbated silty sandstones of facies 1).

Storm event beds are deposited during periods of intense hydrodynamic energy and suppress bioturbation. Sediment is eroded from the bottom by storm-generated waves and currents and is deposited in the lower shoreface and offshore transition zone. Event bed bioturbation is exclusively post-depositional and ichnofabric associations include *Ophiomorpha-Chondrites-Phycosiphon* (laminated sandstones of facies 3 and facies 4), spreiten-burrow (bioclastic sandstones of facies 2), *Thalassinoides-Planolites* (laminated mud-rich beds of facies 4), and *Phycosiphon*-dominated (laminated mud-rich beds of facies 4).

## **2.5 FINING-UPWARD SUCCESSIONS**

Sharp-based fining-upward successions were observed in the study. They consist of laminated sand (facies 3) marked by a basal scour surface, that is gradationally overlain by fining-upward interbeds of sand and mud (facies 4), that subsequently grade into bioturbated silt (facies 5) (Figure 2-11). There is a decrease in grain size and sand bed thickness upwards throughout the succession, as well as an upwards-increase in bioturbation. The fining-upwards successions are further subdivided. The first observed succession consists of subfacies 3a, where the base is commonly marked by a mud clast lag, with the laminated sand beds fining-upwards through to the muddy subfacies 5a, where preserved lenticular bedding is observed (Figure 2-11a). The



second observed succession consists of subfacies 3b and does not contain a mud clast lag at the base. The laminated sand at the base fines upwards through to the intensely bioturbated silt of subfacies 5b, where all physical sedimentary structures are obliterated by bioturbation (Figure 2-11b).

The sharp-based, fining-upward successions are interpreted to be high sediment supply events, deposited during waning energy conditions. The upwards-decrease in grain size suggests a decrease in hydrodynamic energy during deposition. The sharp-based laminated sands (facies 3) indicate rapid sand deposition and are interpreted as storm events deposited in the lower shoreface. The overlying fining-upward heterolithic sand beds (facies 4) indicate deposition under progressively decreasing hydrodynamic conditions. These beds are arranged into bedsets which typically become thinly bedded and increasingly bioturbated. The bioturbated silt (facies 5) that caps these successions represents the lowest depositional energy conditions within the entire succession and is probably the distal expression of fairweather deposits. During interstorm periods, silt and mud are deposited from suspension in the offshore transition zone. The low energy fairweather conditions in this environment promote bioturbation of the fairweather deposits, and possibly post-depositional bioturbation of the preceding storm deposits, as organisms rework the deposited sediments. The mud clast lag at the base of the first observed succession and the lenticular bedding preserved at the top indicates that it was deposited under higher energy conditions than the other succession. The higher energy succession is interpreted to be deposited in a lower accommodation space setting than the lower energy succession, which is capped

by a bed of completely bioturbated siltstone. The fining-upwards successions are interpreted to be deposited in an open marine environment under waning energy conditions.

The upward-fining cycles that characterize this succession seem to represent a progressive, landward shift in facies and are atypical of shallow marine settings where grain size is normally a function of proximity to sediment source and/or paleo-coastline. Generally, shallow marine parasequences prograde and coarsen upwards, displaying a shallowing-upwards trend. Upward-fining packages are usually considered to be channel fill or tidal flat deposits, but we are confident that these successions are deposited in an open marine environment.

Prograding tidal flats display fining-upward parasequences, where a landward shift in facies is represented by the deposition of sand flats, overlain by mixed tidal flats, and capped by mudflats and salt marsh. Sand flats typically display dune cross-bedding, ripple cross-lamination and planar lamination under upper flow regime hydrodynamic conditions. Flaser bedding and lenticular bedding are typically found in mixed flats and mud flats, respectively. Erosionally-based channels, filled with lateral accretion deposits, commonly indicate channel development within tidal creeks in intertidal settings. Tidal flats typically display evidence of subaerial exposure by the presence of dessication cracks within mud beds. Tidal flat deposits may also contain root and plant remains, indicative of their proximity to coastal environments and the prevalence of meteoric porewaters. Due to the extremely stressed palaeoenvironmental conditions

within tidal flats, as a result of repeated episodes of subaerial exposure from tidal activity, and fluctuations in salinity, there is commonly a restricted diversity and abundance of ichnofauna. The majority of these characteristic tidal flat sedimentary structures were not observed within the described cored intervals, and there is no indication of the presence of sand, mixed, or mud flats.

As such, the successions seem to reflect underfilled accommodation space (i.e. deposition in a setting where the rate of accommodation generation is greater than the rate of sediment supply). The controls on such a system would have to be progressive sediment starvation or a series of accommodation creating events, such as syndepositional faulting episodes. The fining-upward successions are interpreted to represent high sediment supply events deposited under waning energy conditions due to a syn-depositional increase in accommodation space (Figure 2-5). A reduction in energy during deposition is indicated by the upwards decrease in grain size and increase in intensity of bioturbation throughout the succession. The association of proximal deposits (facies 3) with increasingly distal deposits (facies 4 and 5) suggests that there are autocyclic controls creating an increase in accommodation space. We consider that the upward-fining trend is a function of rapid locally-created accommodation space, controlled by active faulting during deposition of the succession.

## 2.6 DEPOSITIONAL ENVIRONMENT

The identified facies and subsequent facies associations suggest that the succession was deposited in a transgressive, shallow marine system. The depositional system was characterized by wave-dominated processes, punctuated by episodic storm events that caused significant winnowing of shell beds and transportation of wave-enhanced fluid mud deposits from back-barrier settings onto the open shelf (cf. Dalrymple, 2001). The heterolithic nature of the Ben Nevis succession in the cored interval is consistent with storm event bed deposition in a wave-dominated shoreface setting.

In a wave-dominated shallow marine setting, facies distribution is controlled by the location along the shoreface profile with respect to the positions of fairweather and storm wave bases and mean high- and low-tide levels and to the prevailing hydrodynamic energy conditions (Komar, 1976 and Swift *et al.*, 1986). This differentiates the shoreface into zones that are characterized by particular processes and facies, as identified in the cored intervals (Figure 2-12).

The offshore-transition zone exists between fairweather and storm wave base and is characterized by alternations of low and high energy conditions, where relatively quiet fairweather periods are punctuated by higher levels of storm activity (Komar, 1976 and Swift *et al.*, 1986). The contrast of energy levels is reflected in the facies deposits of the offshore-transition zone as the alternating conditions control sedimentation and bioturbation during storm and interstorm periods.

During interstorm periods, waves do not extend below fairweather wave base and the seafloor in this zone is not disturbed by normal wave action. Fine-grained sediments are deposited from suspension as fairweather deposits. In addition, the low energy conditions promote an infaunal reworking of sediments and the preserved deposits may be fully or partially bioturbated. Fairweather deposits in the offshore-transition zone consist of bioturbated silty mudstone and comprise facies 5. These deposits have the highest mud content and are the most highly bioturbated within the cored interval and are representative of deposition during the lowest energy conditions. These deposits are inter-bedded with higher energy facies that are deposited by episodic storm events.

During storms, higher amplitude waves with a deeper wave base form and the offshore-transition zone may be affected by the storm-generated wave processes. In depths above storm wave base, the seafloor is affected by the storm-induced wave action and currents and higher energy conditions prevail. During storms, eroded sediment in the shoreface may be swept seaward and deposited as beds of hummocky cross-stratified sandstones that are present in the cored intervals as subfacies 3b (Harms *et al.*, 1975; Duke, 1985; and Greenwood and Sherman, 1986). In addition to HCS sandstone beds, storm beds in the offshore transition zone are also represented by the “lam-scam” deposits of facies 4. The laminated beds are deposited by lower energy storm events than the HCS storm beds and are then bioturbated by mostly deposit-feeding organisms as energy wanes. An alternation of planar laminae, diffuse laminae and structureless intervals in facies 4 is interpreted to represent periods of variable

sedimentation rate and is characteristic of the hydrodynamic energy regime in the offshore transition zone. The offshore-transition zone is characterized by storm-generated beds that are inter-bedded with intensely bioturbated beds of silty mudstone that are deposited during fairweather periods and are locally preserved. Within this zone along the shoreline profile, there is an increase in mud and silt content and in degree and diversity of bioturbation in a distal direction.

The shoreface lies between mean low water level and fairweather wave base and is a zone of moderate to high hydrodynamic energy (Komar, 1976 and Swift *et al.*, 1986). Sediment transport is high in the shoreface as the seafloor is continuously agitated by oscillatory and shoaling wave processes in the lower shoreface and also by breaker and surf zone processes in the upper shoreface during fairweather periods. Storm-induced processes erode the upper shoreface, in particular, and storm beds are deposited in a seaward direction in the lower shoreface and offshore-transition zone.

The upper shoreface is characterized by higher energy facies that form predominately under plane bed conditions and moderate energy facies that form as a result of asymmetrical wave action (Komar, 1976 and Swift *et al.*, 1986). In the upper shoreface, there is a winnowing of fine-grained material and the remaining coarser sediment and shell hash are deposited in a landward direction. Facies in the upper shoreface consist of medium to fine-grained sandstone beds with parallel lamination and trough cross-bedding, coquinas and sandstone beds with a high content of

winnowed shell hash. Facies of the upper shoreface are not represented in the cored interval.

Two dominant current systems, longshore and rip currents, are generated by waves in the upper shoreface (Komar, 1976). As waves obliquely approach the shoreline, they break at an angle to the shore and produce circulation cells that create a longshore current that moves sediment parallel to the shore. Rip currents are storm-generated currents that erode channels in the upper shoreface and transport the eroded sediment in a seaward-direction into the lower shoreface or offshore-transition zone.

The lower shoreface may be subdivided into the proximal lower shoreface and the distal lower shoreface on the basis of a landward increase in hydrodynamic energy conditions (Komar, 1976 and Swift *et al.*, 1986). The lower shoreface is dominated by storm deposits as storm-generated waves and currents erode previously deposited fairweather or older storm deposits and subsequently deposit sediment eroded from the upper shoreface. Storm deposits consist of medium to very fine-grained sandstones with HCS bedding of facies 3 and coquinas of facies 2, with a landward-increase in the concentration of reworked shell debris. An amalgamation of storm beds of sandstones with HCS bedding may occur in more agitated environments, forming thick sandstone beds that contain swaly cross-stratification (SCS) (Leckie and Walker, 1982). Fairweather deposits are either not preserved or deposited as a result of the higher energy conditions. The degree of wave influence on the seafloor increases landward and is greater in the proximal lower shoreface than in the distal lower shoreface. The

presence of a sideritized mudstone clast lag at the base of HCS sandstone beds (subfacies 3a) marks an increase in energy and is more common in the proximal lower shoreface.

Fairweather deposits consist of very fine to fine-grained sandstones with silt that are deposited as a result of sedimentation from suspension. During fairweather periods, bioturbation may be reactivated and organisms may rework storm bed deposits following the dissipation of storm conditions or sediment as it is deposited during fairweather conditions and is represented by facies 1 in the lower shoreface. The extent of bioturbation increases in a seaward direction and is greater in the distal lower shoreface. There is an increase in the content of finer-grained sediment and degree and abundance of bioturbation in a seaward direction within the lower shoreface and into the offshore-transition zone. Post-storm reworking of storm beds during fairweather periods may also create ripple cross-lamination, identified at the tops of some HCS storm beds of facies 3, as a result of agitation of the seafloor by fairweather waves.

Within the cored interval, the depositional environment of the fairweather deposits observed in the lower shoreface paleoenvironmental setting is further delineated based on the distribution of shell debris within these deposits. Fairweather deposits of subfacies 1b contain beds of clast-supported shell debris, including oyster and serpulid worm tube fragments. These shell beds differ from those of the coquinas as they are preserved in life position, suggesting low transport distances. The shells may have originated from a lagoon and sourced to the open marine setting via a tidal inlet



channel, where they are transported by ebb-tidal currents and subsequently reworked by wave processes. The presence of shell debris beds in these deposits may indicate deposition in a down-drift direction of the inlet channel, where longshore currents redistribute shells at the mouths of the inlet channels and deposit them further down-drift along the shoreface.

The observed tidal couplets of mud and carbonaceous drapes in storm bed deposits (facies 3) also support the presence of a tidal inlet channel in the paleoenvironmental setting, as fine-grained sediment settles from suspension during alternating high and low slack-water periods. The presence of sideritized mudstone clasts in some of these storm deposits (subfacies 3a) is also consistent with deposition near a tidal inlet channel as these clasts can be produced in back-barrier and lagoonal settings.

The lower shoreface is characterized by storm-dominated deposition and consists of beds of very fine to medium-grained sandstone with hummocky cross-stratification and bioclastic sandstones, which are most prevalent in the proximal lower shoreface. Erosively-based storm beds are inter-bedded with fairweather deposits that are more likely to be preserved in a distal direction along the shoreface profile.

The cored interval shows an overall deepening trend as grain size and sandstone bed thickness decrease upward while the diversity and abundance of trace fossils increase. This is taken to reflect an increase in relative sea level and indicates that the succession was deposited in a transgressive, wave-dominated shoreface setting. The cored interval demonstrates a transition from proximal lower shoreface at the bottom through to

distal lower shoreface to offshore transition zone at the top. It is dominated by HCS storm beds, which are the highest reservoir quality observed, inter-bedded with bioturbated very fine to fine-grained silty sandstones that grade into mud-rich bioturbated beds at the top of the succession.

The deepening trend is also observed in the lateral distribution of facies within the shoreface setting, suggesting a northwest-southeast shoreline orientation with a deepening of water towards the northeast. The Hebron Field represents the most proximal depositional setting of the system and the most distal setting is represented by the Ben Nevis Field. Storm beds dominate the cored interval in the Hebron Field and indicate a high energy paleodepositional environment that is representative of a proximal lower shoreface setting. The Hebron wells are dominated by HCS storm beds and occasional coquinas. The Hebron Field is less heterolithic than the more distal blocks as the HCS beds are more amalgamated with fewer interbeds of bioturbated fairweather deposits present. There is no presence of distal muds within these wells and occurrences of the “lam-scram” facies are rare, which are more distally-deposited facies. Fluid mud deposits identified in Hebron M-04 and Hebron D-94 contain sedimentary fabric and the paucity of bioturbation reflects an agitated environment, suggesting deposition in a proximal depositional environment.

As the depositional environments become more distal towards the northeast, the West Ben Nevis and Ben Nevis fields are dominated by facies that indicate a transition into distal lower shoreface and offshore transition zone environments, with Ben Nevis L-55

representative of the most distal environment within the cored interval, having the only occurrence of distal muds. The succession becomes more heterolithic in a basinward direction as the water deepens and hydrodynamic energies decrease and become more variable. HCS storm beds become thinner and are more inter-bedded with finer-grained and more bioturbated fairweather deposits. The most distal fairweather deposits in the Ben Nevis Field have a higher silt and mud content and abundance and diversity of trace fossils, indicating a more quiescent depositional environment. There is an increase in deposit-feeding trace fossils in the more distal facies, as the *Cruziana* ichnofacies becomes more common than the *Skolithos* ichnofacies in deeper environments. Fairweather deposits and “lam-scram” deposits become more prevalent towards the northeast, as the paleoenvironments become less agitated as water depths increase. Interstorm periods in the more distal zones along the shoreline profile are characterized by lower hydrodynamic energies and preserve deposition of beds and promote bioturbation.

## **2.7 RESERVOIR QUALITY CONTROLS**

Shoreface environments are extensive in nature and facies belts in these settings are widespread and laterally continuous. The orientation of facies belts are aligned parallel to the paleo-coastline and reservoir quality degrades distally along a shoreline-perpendicular trend. Facies belts in a shoreface setting may extend for several kilometers along strike and up to 1000's of meters in the dip direction. The presence of

inter-bedded siltstones and mudstones creates heterolithic zones of low-permeability, vertically and laterally, potentially creating barriers or baffles against fluid flow. For optimal development planning, it is critical to understand the controls on reservoir quality and to predict the distribution and impacts of low-permeability heterogeneities.

Within the Hebron Asset, there is a lateral and stratigraphic variation in reservoir quality of the Ben Nevis Formation as the reservoir becomes more heterolithic and finer-grained as paleoenvironments become more distal due to allocyclic and autocyclic controls on water depth. A rise in sea level and an increase in water depth along the shoreline profile and in the downthrown blocks of growth faults increase the accommodation space within the depositional setting. Increased accommodation space in a shoreface setting, where the rate of accommodation generation is greater than the rate of sediment supply, creates a transition into lower energy environments with more distal facies deposits. As depositional settings become more distal, deposits become increasingly more inter-bedded and contain more finer-grained, mud-rich and bioturbated facies.

The Ben Nevis Formation is aggradational to progradational at the base and becomes retrogradational at the top, as sea level rises and the formation transgresses into the overlying Nautilus Shale. The lower part of the cored interval is dominated by high quality HCS sandstone storm beds and becomes progressively more inter-bedded with lower quality fairweather deposits towards the top of the succession. There is a large regional variation in reservoir quality across the Hebron Asset as net-to-gross decreases

from the Hebron Field through to the West Ben Nevis Field and to the Ben Nevis Field. The most proximal facies are observed in the I-13, D-94, M-04 and H-71 wells as they contain more high energy, coarser-grained deposits. More finer-grained, distal deposits are observed in the B-75 and L-55 wells, with L-55 being the only well to contain distal mud deposits in the cored interval. The average horizontal permeability, ranges from a low of 0.1 mD in the Ben Nevis Field to a maximum of 400 mD in the Hebron Field (C-NLOPB, 2012).

The reservoir rock also contains an abundant amount of calcite cement that is considered a secondary diagenetic component and can strongly degrade reservoir quality. Within the cored interval, calcite-cemented zones are observed in two forms: 1) Calcite concentrated within coquina shell bed deposits (facies 2); and 2) Nodular concretions that have irregular boundaries and rounded edges in core. The observed nodular concretions are randomly distributed throughout the succession and tend to be concentrated within the higher reservoir quality HCS sandstone storm beds (facies 3). There are minor occurrences within the lower quality facies, including the bioturbated very fine to fine-grained sandstone with silt (facies 1) and the “lam-scram” deposits (facies 4). The nodules are several centimeters in thickness in the cored interval and are believed to be of limited areal extent. Since calcite-cements reduce the porosity and permeability of the host facies, thereby affecting in-place hydrocarbon volumes and possibly fluid flow during production, it is important to incorporate them into facies and reservoir models.

## 2.8 CONCLUSIONS

The Ben Nevis Formation at the Hebron Asset is interpreted to be a transgressive, wave-dominated shoreface succession that is punctuated by episodic storm events. Six facies were identified within the cored interval in the succession and used to identify proximal lower shoreface, distal lower shoreface and offshore transition zone depositional environments. The identified facies were classified as either fairweather deposits or storm deposits, reflecting the dynamic energy regime that exists in a shoreface setting that is affected by wave and storm activity. The storm deposits have the highest reservoir quality and understanding the distribution of facies belts aids in their prediction.

Shallow marine systems are marked by alternations between fairweather and storm conditions. The prevailing conditions, in association with water depth, influence deposition and bioturbation on the sea bed and control facies distribution along the shoreface. Background sedimentation occurs during fairweather conditions and only zones that lie above storm wave base may be influenced by wave processes. The sea bed becomes less agitated as zones become deeper and lower hydrodynamic energies support deposition of finer-grained sediments from suspension and bioturbation. Although storm activity is intermittent and brief, much of the higher quality facies are deposited within the shoreface under these high energy episodes. The heterolithic nature of shoreface deposits reflects the alternation of fairweather and storm conditions.

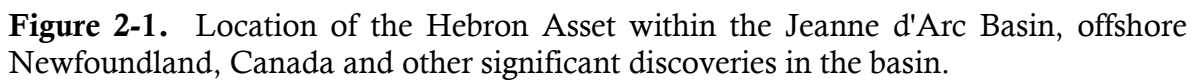
As environments become more distal within a shoreface environment, water depths increase and the influence of wave activity on the seafloor decreases. A rise in sea level, increases in bathymetry along the shoreline profile and downthrown syndepositional fault blocks contribute to increases in water depth and a transition into more distal environments. Distal facies belts contain more finer-grained deposits that are mud-rich and highly bioturbated and are more heterolithic than more proximal facies belts.

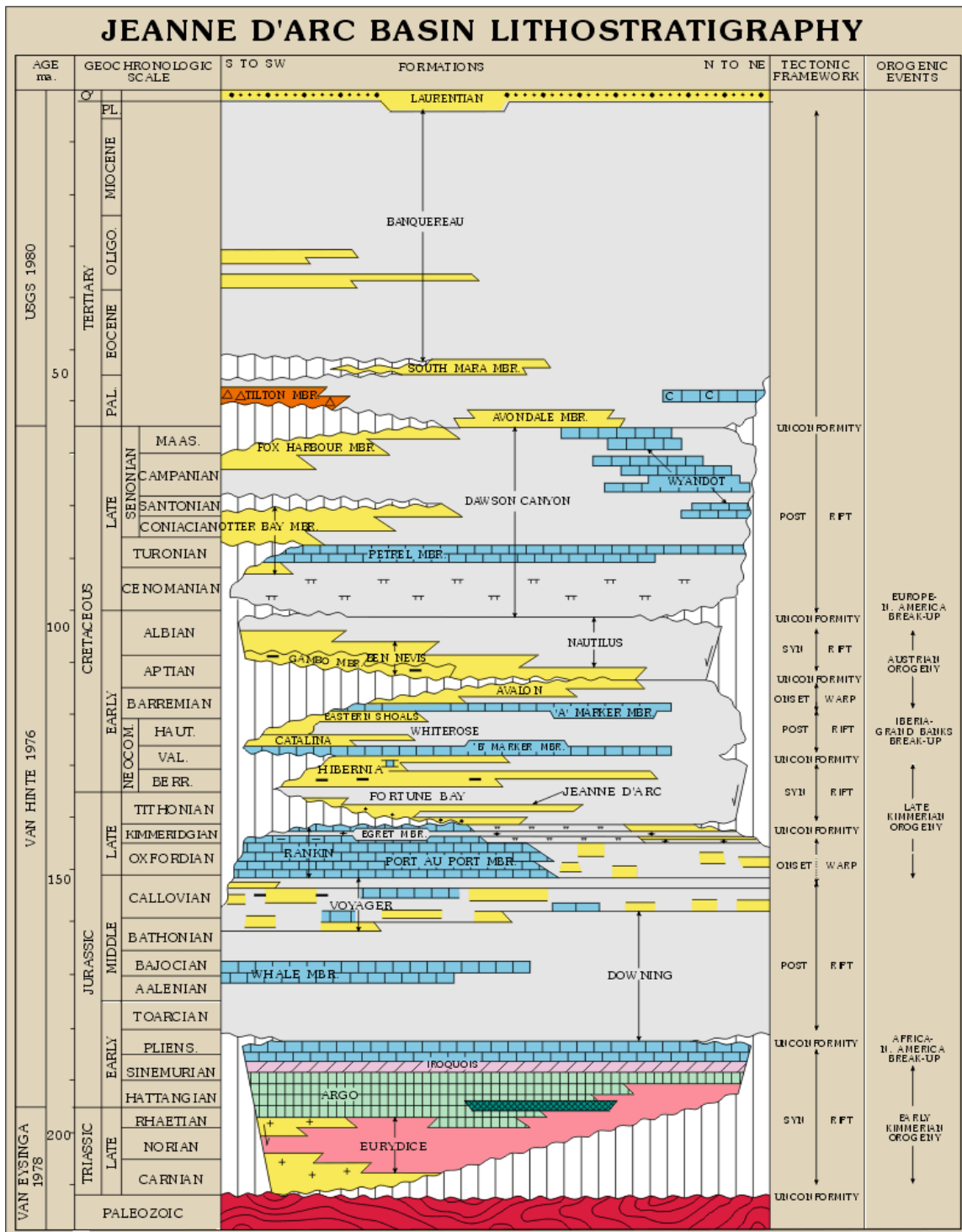
The shoreline orientation of the paleoenvironment of deposition is inferred to have a northwest-southeast orientation with facies belts transitioning into more distal environments in a northeast direction towards the Ben Nevis Field. Within the Hebron Asset, there is a reduction in net-to-gross from the Hebron Field to the West Ben Nevis Field and to the Ben Nevis Field. The dominant environment of deposition in the Hebron Field is proximal lower shoreface and the I-13, D-94 and M-04 wells are dominated by higher quality HCS sandstone storm beds and have the highest net-to-gross within the setting. Storm bed thickness decreases and become more inter-bedded with finer-grained and bioturbated fairweather deposits as there is a transition into the distal lower shoreface environment in the West Ben Nevis Field and the offshore transition zone in the Ben Nevis Field. The L-55 well is the most heterolithic of the studied succession and was the only well to contain distal mud facies. The succession displays a landward shift in the deposition of more distal facies and displays an overall-deepening trend.

**Table 2-1.** Sedimentary and ichnological description of the facies observed in the core study of 6 wells that penetrated the Ben Nevis Formation in the Hebron Asset and their associated depositional environment.

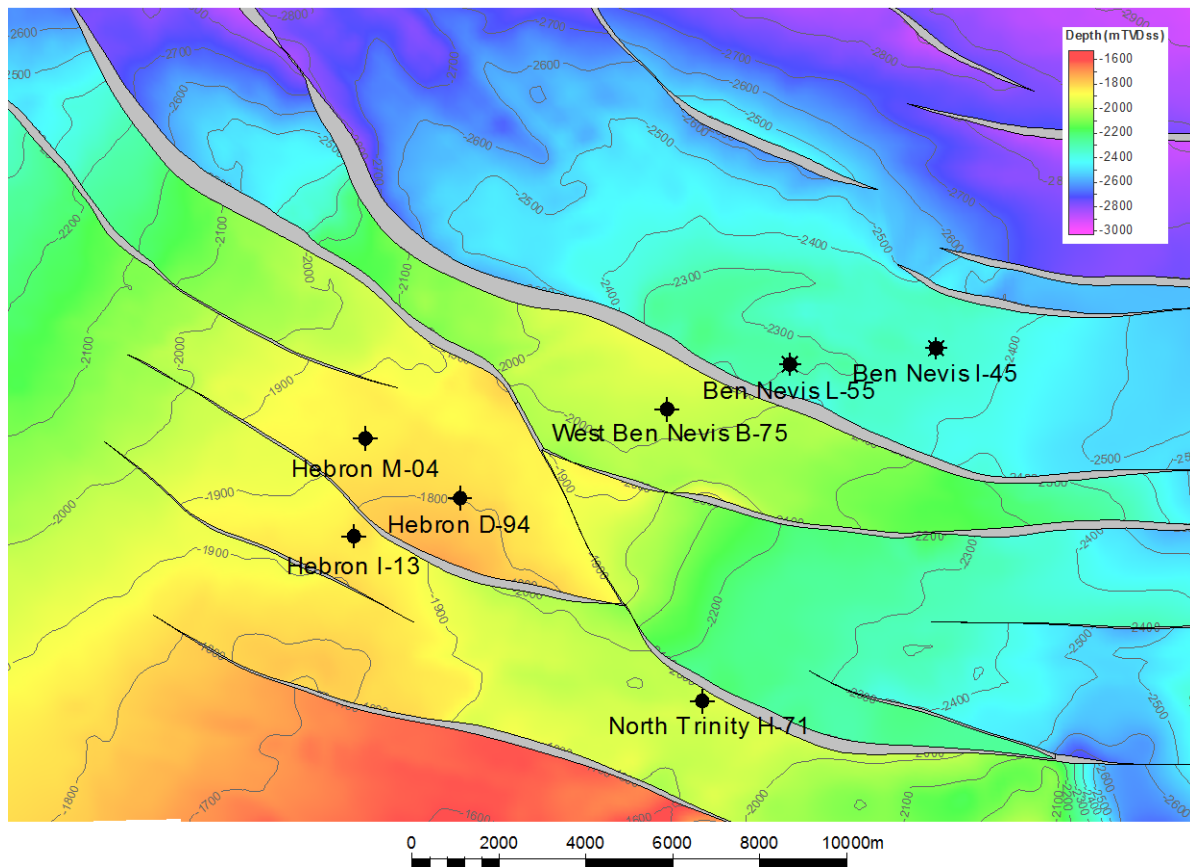
Facies	Characteristics	Bioturbation	Bedding Thicknesses	Depositional Environment
Bioturbated silty mudstone	Mudstone, siltstone, intensely bioturbated (BI 60-90%). Internal depositional structures not preserved. Commonly caps small-scale lining-upwards successions.	<i>Optiomorpha</i> , <i>Phycosiphon</i> , <i>Teichichnus</i> and <i>Asterosoma</i>	Bedsets up to 1 m thick	Fairweather deposit in Offshore-Transition Zone
Inter-bedded sandstone and mudstone	fgL to vfgU sandstone inter-bedded with mudstone, moderately bioturbated (BI 30-60%). Planar to wavy-laminated beds grade into bioturbated beds, forming this facies "lam-scrum". Angular, sideritized mud-flake breccias sometimes form a basal lag.	<i>Optiomorpha</i> , <i>Chondrites</i> , and <i>Phycosiphon</i>	Beds are cm-scale thickness	Moderate energy storm deposit in Offshore-Transition Zone
Bioturbated and Laminated Mudstone	Inter-bedded mudstone, fg sandstone stringers. Mudstone beds are laminated and contain sharp-margined, sand-filled <i>Glossifungites</i> .	<i>Thalassinoides</i> isp.	Beds are 2-5 cm thick	Fluid mud deposit
Bioturbated Sandstone	fgL to vfgU sandstone, siltstone, highly bioturbated (BI 60-70%). Component of carbonaceous debris. Internal depositional structures not preserved. Bioclastic components are present (fragments of serpulid worm tubes and oyster shell debris).	<i>Optiomorpha</i> , <i>Planolites</i> , <i>Teichichnus</i> , and <i>Phycosiphon</i>	Beds are under 1 m thick	Fairweather deposit in Lower Shoreface
Bioclastic Sandstone	Matrix supported (fg sandstone) lag deposited on scoured surface. Massive in appearance with no bedding features. Lag consists of bioclastic components (fragments of serpulid worm tubes, bivalves and gastropods). Sometimes cemented with diagenetic calcite.	N/A	Beds are up to 3 m thick	Storm deposit in Proximal Lower Shoreface
Laminated Sandstone	fgL to vfgU sandstone, well sorted, with parallel to low angle lamination. Ripples or ripple cross-bedding may be observed at the tops of beds. Clay drapes and carbonaceous are commonly deposited along laminae. Lag deposits of sideritized mudstone rip-up clasts are common along basal scour contacts. Commonly overlies and is associated with bioclastic sandstone facies.	N/A	Bed thicknesses range from a few cm to m-scale thicknesses	Distal Lower Shoreface (analgamated beds) to Offshore-Transition Zone (interbedded with fairweather deposits)



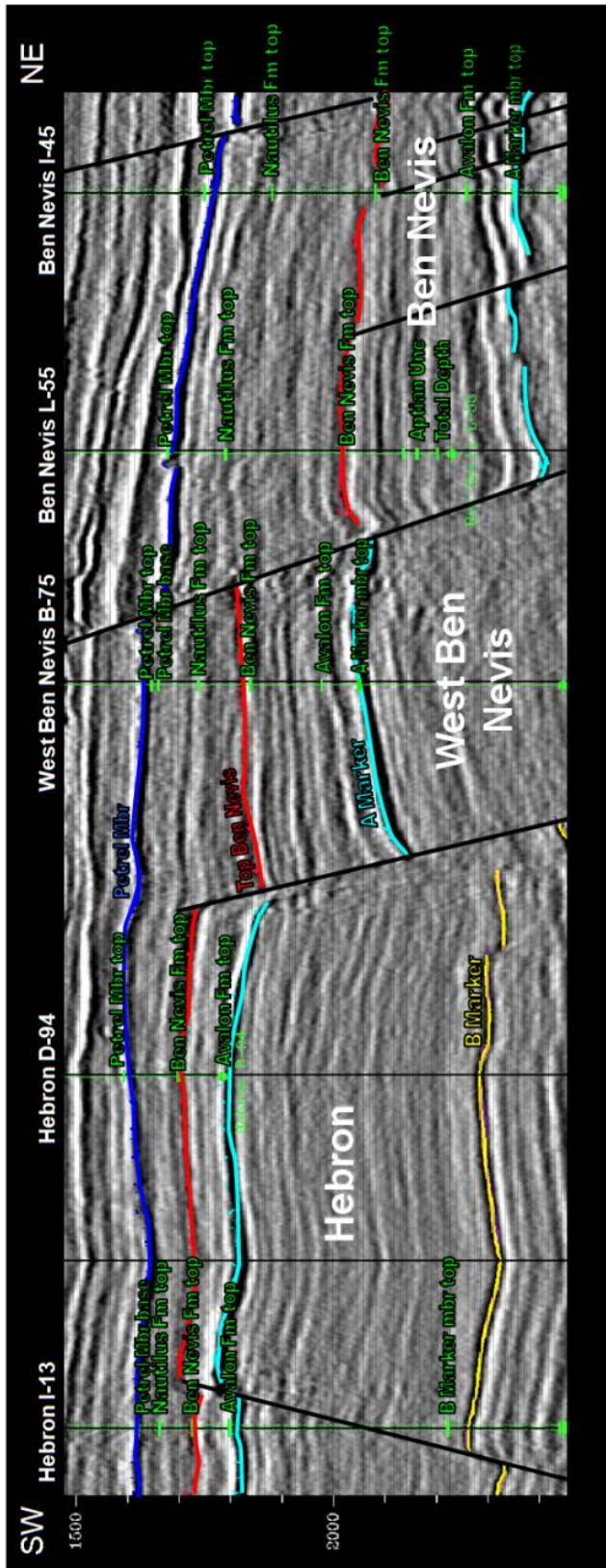




**Figure 2-2.** Lithostratigraphic chart of the Jeanne d'Arc Basin.

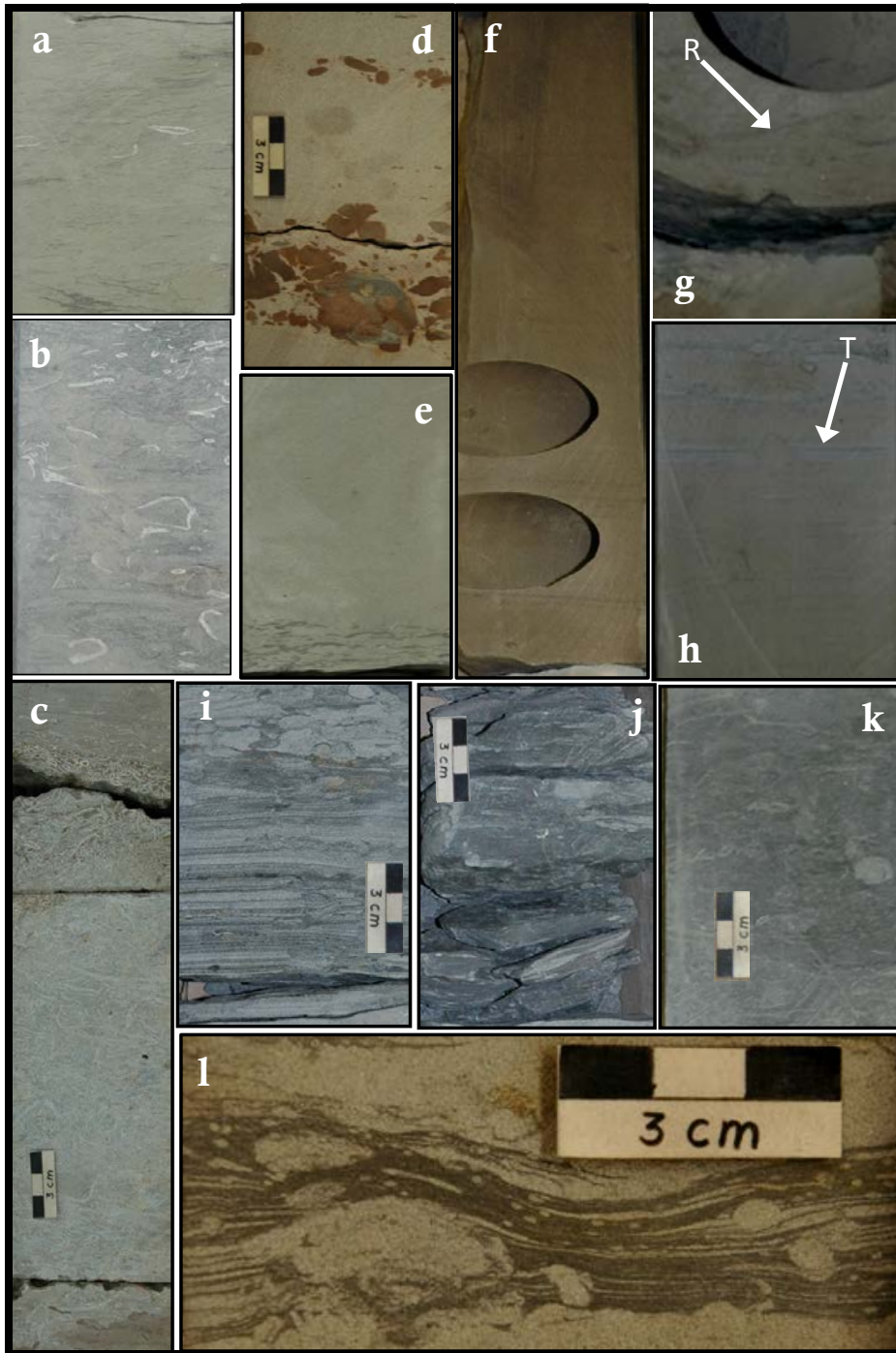


**Figure 2-3.** Depth-structure map of the Hebron Asset of the top of the Ben Nevis Formation with the locations of the seven wells included in this study.

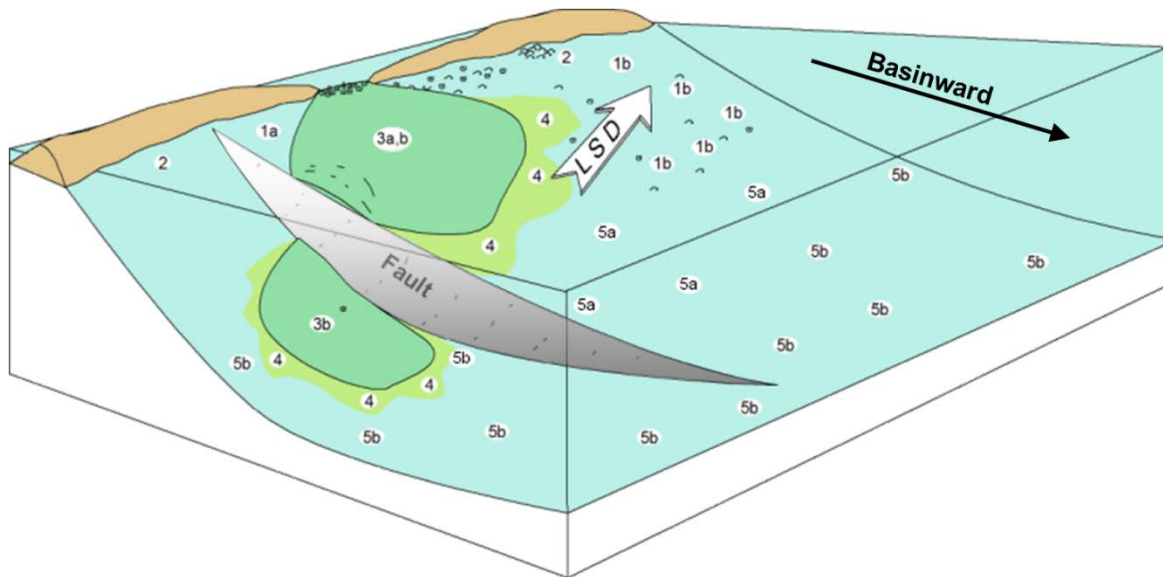


**Figure 2-4.** SW-NE seismic section through the Hebron, West Ben Nevis and Ben Nevis blocks, showing a thickening of the Ben Nevis Formation towards the north-east in the Hebron Asset.

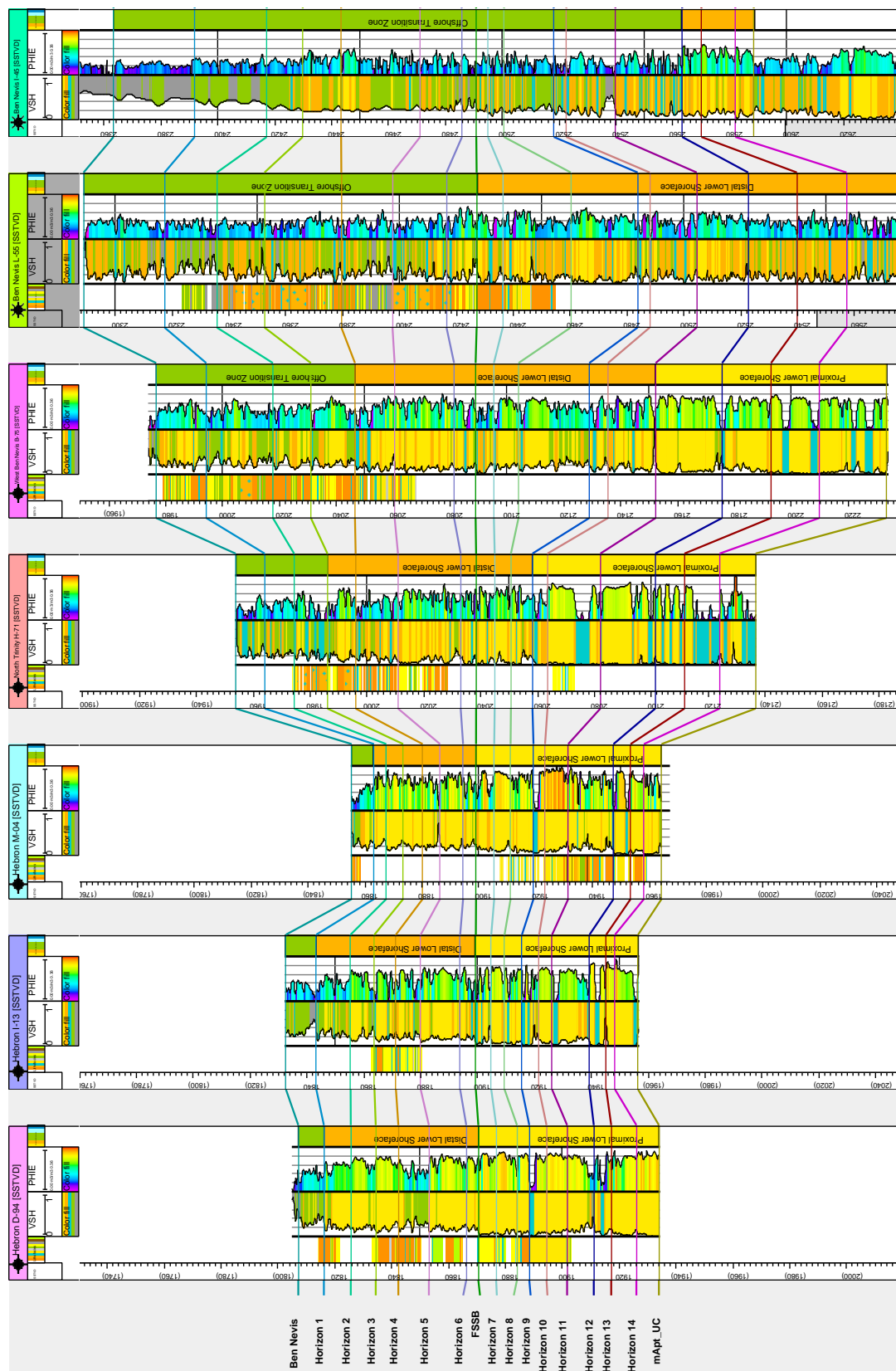


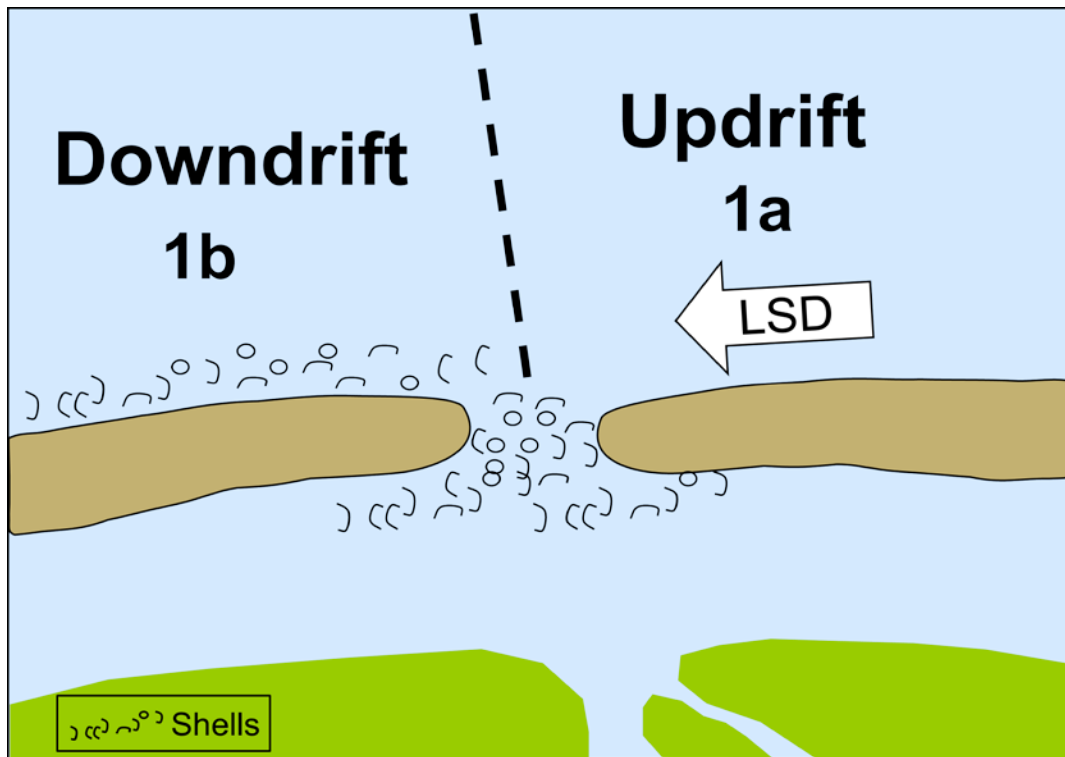


**Figure 2-5.** Sedimentary facies classified in core from 6 wells studied in the Hebron Asset: (a) facies 1a; (b) facies 1b with scattered shells; (c) facies 2; (d) facies 3a with sideritized mud clast lag; (e) facies 3a with mud drapes; (f) facies 3b; (g) ripple-cross lamination (R) and (h) tidal couplets (T) in facies 3; (i) facies 4; (j) facies 5a with lenticular bedding; (k) facies 5b; and (l) facies 6 with *Glossifungites* surface.



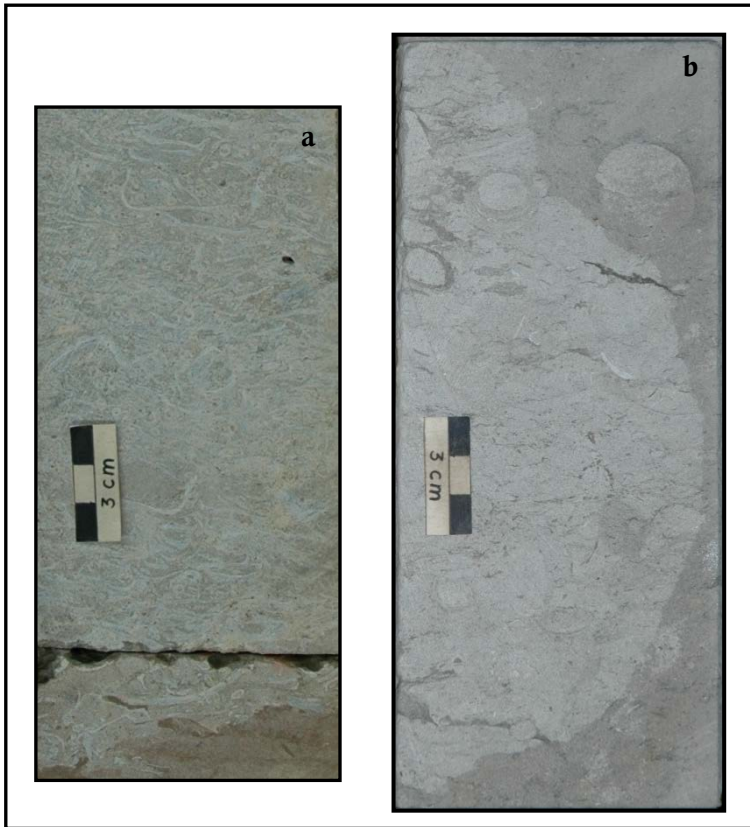
**Figure 2-6.** Schematic of the interpreted depositional environment of the Ben Nevis Formation in the Hebron Asset. The reservoir is interpreted to be deposited on a wave-dominated shoreface near a tidal inlet channel, where longshore drift (LSD) redistributes lagoonal-sourced shells across the shoreface in a downdrift direction. Active faulting results in the deposition of a more distal expression of facies.



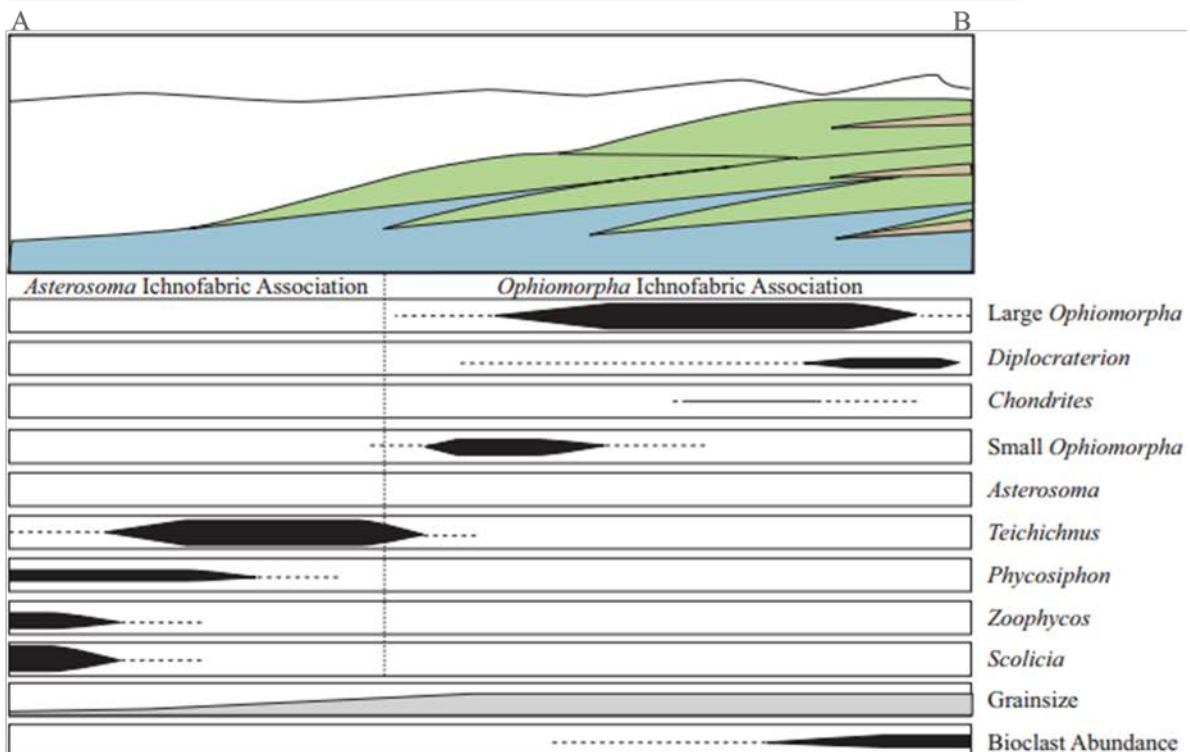
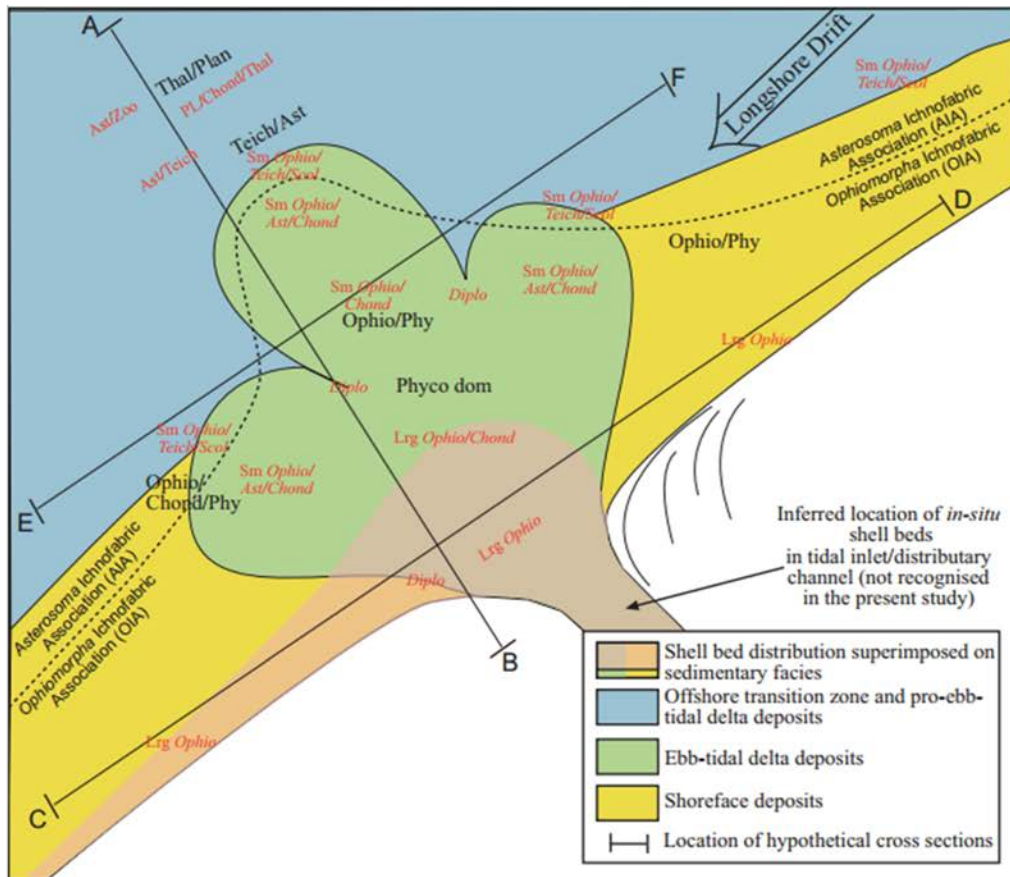


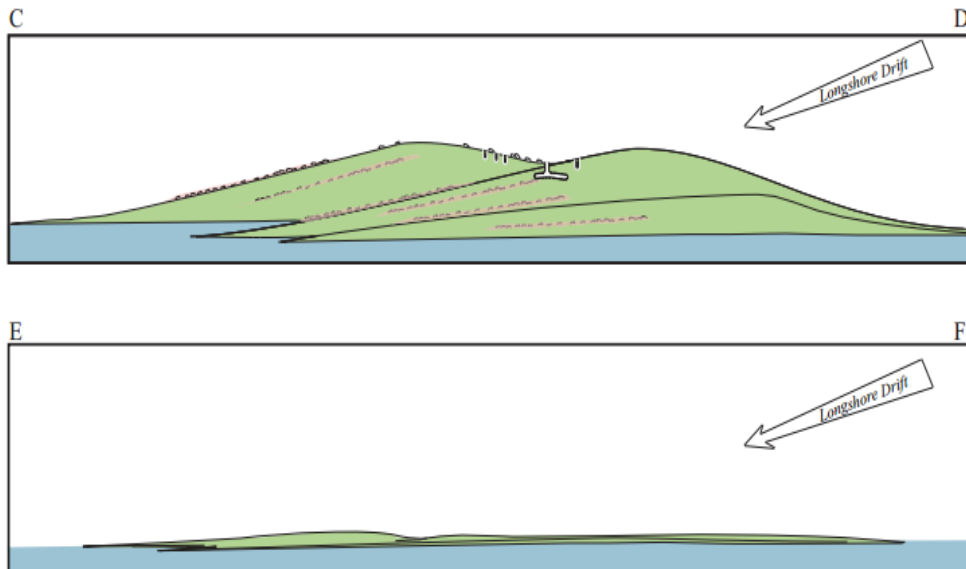
**Figure 2-8.** The two different patterns of shell debris within facies 1 suggest that the shells may be sourced from a lagoon by ebb-tidal currents into an open marine setting and reworked by shoreface currents. Shells are redistributed down-drift of an inlet channel by longshore drift (LSD) currents and are present in facies 1a.



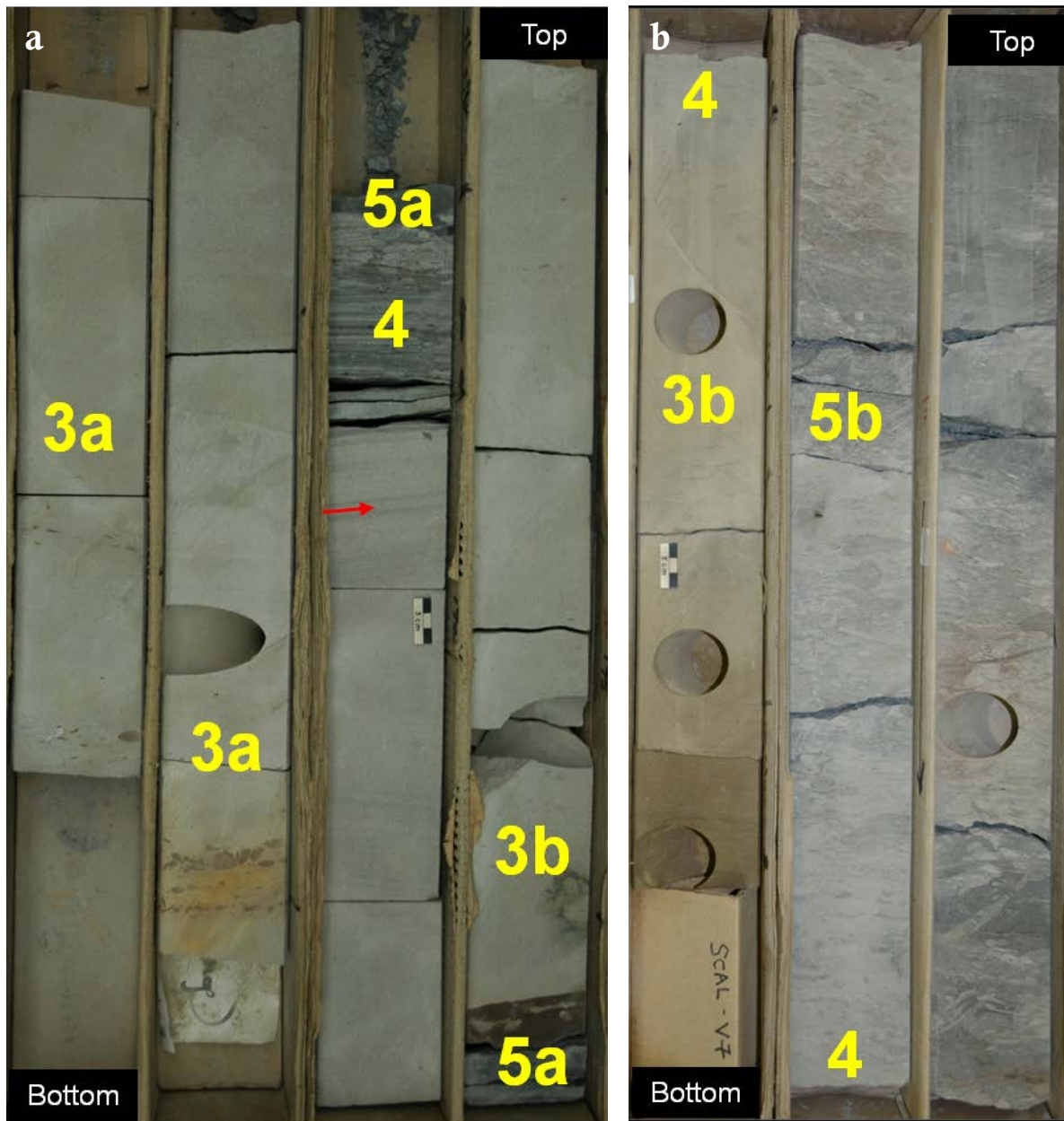


**Figure 2-9.** Calcite cement observed in core from the Ben Nevis Formation in Ben Nevis L-55. (a) Calcite concentrated within coquinid shell bed deposits. (b) Rounded and irregular nodular boundaries cross-cut the host facies.

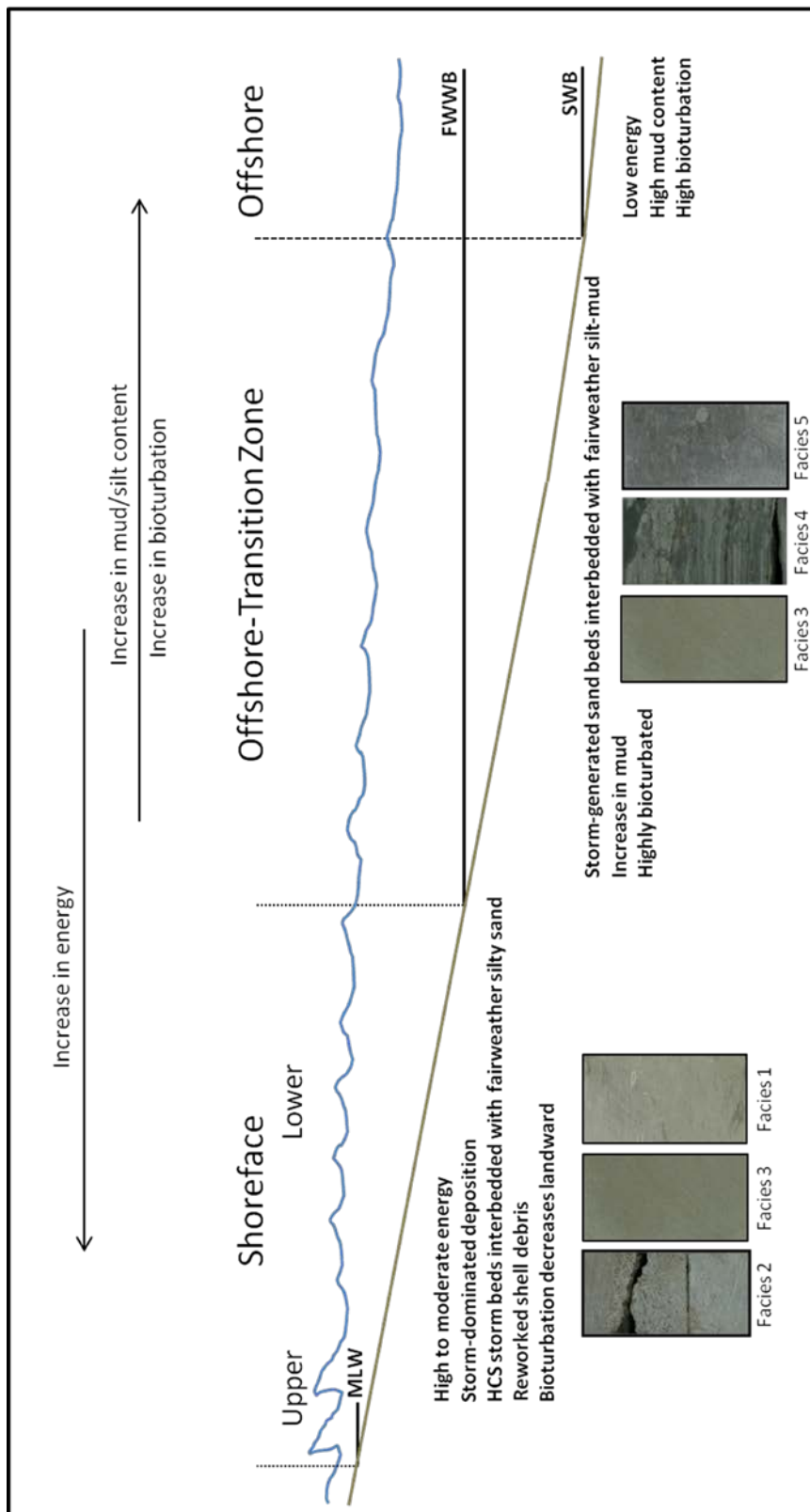




**Figure 2-10.** Ichnofabric associations within a wave-dominated shoreface setting, such as that interpreted as the environment of deposition for the Ben Nevis Formation at the Hebron Asset.



**Figure 2-11.** Fining-upwards successions observed in core in the Ben Nevis Formation in the Hebron Asset that consist of facies 3 grading upwards into facies 4 and facies 5. The successions display an upwards-decrease in grain size and sand bed thickness and an increase in bioturbation. They are interpreted to be high sediment supply events, deposited during waning energy conditions. They are further subdivided into those that contain (a) facies 3a, 4 and 5a and (b) facies 3b, 4 and 5b.



**Figure 2-12.** A schematic profile of a wave-dominated shoreline profile showing the subenvironment zones and associated facies. MLW – mean low water level, FWWB – fairweather wave base, and SWB – storm wave base. (After Reading and Collinson, 1996).

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### **3 Using Outcrop Data to Model Calcite Cementation in a Shoreface Reservoir, Ben Nevis Formation, Hebron Asset**

#### **3.1 INTRODUCTION**

Accurate simulation of fluid behaviour during production in hydrocarbon reservoirs requires a realistic prediction of reservoir continuity and distribution of reservoir properties. Reservoir heterogeneity is created by both depositional and diagenetic processes, producing vertical and lateral variations in porosity and permeability. Grain size, sorting, bioturbation, and diagenetic cements strongly control reservoir quality and heterogeneity within sedimentary successions. An understanding of the architecture of facies and the distribution of diagenetic cements is important in reservoir characterization, as this is what defines the distribution of flow units that control reservoir performance and hydrocarbon recovery (Begg *et al.*, 1992; Flint and Bryant, 1993; Rosvoll *et al.*, 1997; and White *et al.*, 2004).

The precipitation of carbonate cements in sandstone reservoirs is a common post depositional diagenetic process that occurs during burial and causes a significant degradation in reservoir quality (Cant and Ethier, 1984; McBride, 1989; Amthor and Okkerman, 1998; Molenaar, 1990; Morad, 1998; Willis and White, 2000; Dutton *et al.*, 2002; White *et al.*, 2003; and Dutton, 2008). Carbonate cements can form concretions within the host rock, producing impermeable ("tight"), isolated bodies that act as macroscopic heterogeneities creating baffles or barriers to fluid flow (Willis and White, 2000; Dutton *et al.*, 2002; and White *et al.*, 2003). The ability to

incorporate the distribution, size and geometry of the non-reservoir bodies into reservoir models improves the prediction of reservoir quality and flow performance (Sweet *et al.*, 1996 and Pranter *et al.*, 2005). It is however, notoriously difficult to incorporate carbonate cements in a logical manner due to the lack of a rationale. Providing the rational basis for this decision-making in reservoir characterization and modelling is the focus of this study.

Within the subsurface, the lateral continuity of low permeability cements is difficult to characterize and model, as the cements are commonly concentrated in concretions of limited lateral extent at the interwell-scale. However, concretions are readily apparent in outcrop and exposures display a lateral reservoir-scale distribution of the diagenetic heterogeneity features. Detailed analysis of concretions in outcrop provides information with respect to their dimensions and distribution and has the potential to supplement subsurface data sets in creating reservoir models to assess their impact on fluid flow (Ciametti *et al.*, 1995; Dutton *et al.*, 2000; Willis and White, 2000; Dalrymple, 2001; and Dutton *et al.*, 2002).

In this study, calcite concretions were mapped in two exposures of shallow marine deposits in the Book Cliffs, Utah. Data were collected with respect to the stratigraphic occurrence and architecture of calcite-cemented zones within the well-exposed parasequences of shoreface outcrops. The dimensions and spatial distributions of the concretions were mapped and used to create an outcrop analog

data set of calcite cementation in shoreface deposits. The outcrop analog provides geostatistical data that can be applied in analogous reservoir models for modelling the distribution of calcite cement and assessing its impact on fluid flow.

The Ben Nevis Formation in the Hebron Asset, in the Jeanne d’Arc Basin, offshore Newfoundland, contains heavily calcite-cemented zones that occur within highly porous shoreface sandstones. Well log and core data provide information about the stratigraphic occurrence of calcite cements within the formation, but uncertainty remains in lateral continuity and interwell-interpolation. Outcrop analog data collected in this study was calibrated to the borehole data to estimate the spatial distribution of calcite cement within the reservoir. This creates a reservoir model that better captures the distribution of these macroscopic heterogeneities and that is suitable for simulating fluid flow.

## **3.2 HEBRON ASSET**

### **3.2.1 Geological Setting**

The Hebron Asset is located in the Jeanne d’Arc Basin, offshore Newfoundland, Canada (Figure 3-1). The extensional basin is host to many prolific hydrocarbon reservoirs, including the Hibernia, Terra Nova and White Rose fields. The Hebron Asset consists of the Hebron, West Ben Nevis and Ben Nevis fields (Figure 3-2) and is classified as a significant discovery that is estimated to contain 3176 MMbbls of oil (C-NLOPB, 2012).

At the Hebron Asset, six exploration and delineation wells targeted the Ben Nevis Formation (Figures 3-2 and 3-3). Log and core data indicate a transgressive sequence of shoreface siliciclastic facies that alternate between fairweather and storm deposits. The Ben Nevis Formation consists of stacked shoreface parasequences that demonstrate a gradual net fining-upwards trend through the formation. The base of the formation is dominated by proximal lower shoreface parasequences and there is a net transgression through to parasequences dominated by distal offshore facies at the top of the formation. The lower interval of aggradationally-stacked parasequences immediately overlie the mid-Aptian unconformity, and consist of amalgamated storm deposits. A change in the depositional pattern occurs in the upper Ben Nevis Formation in response to sea level rise and an increase in subsidence rate and is marked by a transgressive surface of erosion. There is an increase in the preservation of finer-grained sediments in the upper part of the formation and parasequences display a retrogradational stacking pattern as the depositional environment becomes increasingly distal due to the rate of accommodation generation being greater than the rate of sediment supply.

Throughout the basin, the Ben Nevis Formation consists of clean sandstones interbedded with bioturbated argillaceous and silty sandstones and siltstones (Harding, 1988; Hiscott *et al.*, 1990; Sinclair, 1993; Pemberton *et al.*, 2001; and Tonkin *et al.*, 2010). The heterolithic nature of the Ben Nevis Formation in the Hebron Asset reflects deposition in a more shoreline-distal depositional setting, preserving evidence

of highly variable hydrodynamic energy conditions not recorded in regions with parasequences dominated by amalgamated hummocky cross-stratification (HCS), such as the Hibernia Field (Sinclair, 1993 and Pemberton *et al.*, 2001). The highest quality reservoir facies in the Hebron Asset also contain hummocky cross-stratification and are commonly marked by a scour surface or a basal lag, but are inter-bedded with lower permeability offshore transition zone facies (as described in the preceding chapter). These characteristics suggest that they are produced by storm activity or pulses of shoreface progradation that periodically supplied large amounts of sediment to the otherwise quiescent depositional setting. Bioturbated interbeds of finer-grained deposits suggest deposition during lower energy, fairweather conditions (Chapter 2). Trace fossil assemblages within these deposits are indicative of normal marine conditions (Tonkin *et al.*, 2010).

The Ben Nevis reservoir in the Hebron Asset contains an abundant amount of diagenetic calcite cement. Core-based study allows recognition of at least some of these as nodular concretions, while others are centred on highly cemented coquina shell bed deposits (Figure 3-4). This is represented in the associated petrophysical well logs as intervals that are clean (0-30% volume of shale) and have low porosity and permeability. The concretions tend to be concentrated within higher reservoir quality host rocks and are several centimetres to metres in thickness and are believed to be of limited areal extent, based on an understanding of their distribution in outcrop. Since calcite cements strongly degrade reservoir quality and act as obstacles

to fluid flow, it is critical to accurately predict their geometry and distribution in reservoir models.

### **3.2.2 Facies**

For the purposes of reservoir characterization and modelling, facies were recognized in core and on petrophysical well logs on the basis of distinct reservoir properties and are classified as either fairweather or storm deposits (Table 3-1 and Figure 3-5).

#### ***Bioturbated silty mudstone***

The bioturbated silty mudstone facies is intensely bioturbated (60-90% bioturbation intensity) and contains the most abundant and diverse trace fossil assemblage. The ichnofaunal assemblage is dominated by *Ophiomorpha* and also includes *Phycosiphon*, *Teichichnus*, and *Asterosoma*. This facies occurs in bedsets up to 1 m thick and has the lowest reservoir quality in the formation. It is most abundant in the top of the succession and commonly caps small-scale fining-upwards successions. This facies is interpreted to represent a fairweather deposit in the offshore-transition zone.

#### ***Bioturbated Sandstone***

The bioturbated sandstone facies consists of very fine to fine-grained sandstone and has a component of siltstone, as well as carbonaceous debris, which reduce the reservoir quality. There is a high degree of bioturbation (60-70% bioturbation intensity) with no preservation of physical sedimentary structures. The ichnofaunal

assemblage is diverse, including *Planolites*, *Teichichnus*, and *Phycosiphon*, and is dominated by *Ophiomorpha*. Shell debris is present, of which oyster shells and serpulid worm tubes are the dominant components in the lower and upper intervals of the formation, respectively. Beds are typically less than 1 m in thickness. This facies is interpreted to represent a fairweather deposit in the lower shoreface.

### ***Bioclastic Sandstone***

The bioclastic sandstone facies is a lag deposit that consists of clast-supported shell beds within a fine-grained sandstone matrix. The coquina shell beds are highly winnowed and contain abundant bivalves, gastropods and serpulid worm tubes. Oyster shells are the dominant component of the shell beds in the lower interval of the formation, while the upper interval is dominated by serpulid fragments. Beds are up to 3 m thick and are sometimes cemented with diagenetic calcite. The coquina shell beds have an erosive basal contact and are commonly overlain by the laminated sandstone facies and are interpreted to represent the initial scouring of a storm event in the proximal lower shoreface.

### ***Laminated Sandstone***

The laminated sandstone facies consists of very fine to fine-grained sandstone with parallel to low-angle lamination that may pass upwards into ripples or ripple-crossbedding at the top of the beds. Clay drapes and carbonaceous debris are commonly associated with the laminae. The low-angle lamination is characteristic of

hummocky and/or swaley cross-stratified deposits. Lags of sideritized mudstone rip-up clasts are commonly present along basal scour contacts. Bed thicknesses vary from a few centimetres thick up to metre scale thicknesses. Thickness intervals that are greater than a metre typically represent an amalgamation of several beds of this facies. The laminated sandstone facies is interpreted to represent storm event beds and the location of deposition along the shoreline profile is differentiated by its association with overlying beds. Where intervals of this facies are present as amalgamated beds, they represent storm deposition in the proximal lower shoreface. Below fairweather wave base, finer-grained deposits are preserved between storm events. This facies represents storm-induced deposition in the distal lower shoreface to offshore-transition zone when inter-bedded with fairweather deposits. This facies has the highest reservoir quality in the succession.

### **Calcite Cementation**

Calcite-cemented zones were observed in a detailed core study of the Ben Nevis Formation in the Hebron Asset (described in the preceding chapter). Cores from five wells and one offset well contain an abundant amount of calcite cement that is either concentrated within coquina shell bed deposits or present in nodular form with rounded, irregular boundaries that cross-cut the host facies (Figure 3-4). The nodular boundaries do not coincide with any sedimentological changes or structures, facies boundaries, or erosional surfaces. The cemented intervals are concentrated within



the higher quality laminated sandstone facies throughout the cored interval. Minor occurrences of the nodular cements were also observed in the bioturbated sandstone facies. The nodules are several centimetres to decimetres in thickness, ranging from a few centimetres to roughly 3 m in thickness, although the higher thicknesses may be a local amalgamation of multiple nodules.

### **3.3 OUTCROP ANALOGUE**

Calcite concretions are common diagenetic features within shoreface deposits exposed in the Book Cliffs, Utah. The concretions are composed of ferroan dolomite and are clearly visible in outcrop exposures because of their orange colour due to weathering from the oxidation of iron (Figure 3-6). This allows for large-scale mapping of these discrete cemented bodies as they are easily distinguished from the uncemented or poorly cemented host rocks.

Continuous exposures of cliff faces in the Book Cliffs provide an exceptional cross-sectional view of shallow marine deposits. This enables an understanding of the spatial distribution of the heterogeneity produced by calcite concretions at the interwell-scale that cannot be quantified by subsurface data. The aim of this field study was to determine the size and distribution of calcite concretions within shoreface deposits for use as an analog model for the distribution of cementation in the Ben Nevis Formation in the Hebron Asset at the interwell-scale.

To quantify the size and distribution of calcite concretions, exposed sections of the Emery Sandstone Member were studied at two outcrop locations in the Book Cliffs (Figures 3-7 and 3-8). Calcite concretions were measured in progradational shoreface systems of the Emery Sandstone Member in exposed cliff faces in Garley Canyon and Carbonville, near Price, Utah. Data acquired from the outcrops include measured sections of the exposures and field sketches and photomosaics of the cliff faces, which allowed for the detailed mapping of the concretions. The photomosaics were tied to the measured sections, field sketches and vertical markers along the cliff faces to create digital outcrop maps. The outlines of the concretions, flooding surfaces and boundary surfaces were marked by polygon traces on the outcrop maps and used to measure the size and distribution of concretions and for sampling onto a rectangular modelling grid for geostatistical analysis.

### **3.3.1 Geological Setting of the Study Area**

The Emery Sandstone Member of the Mancos Shale is a wave-dominated shoreface deposit that prograded into the Western Interior foreland basin of the Sevier Orogeny during the Cretaceous (Matheny and Picard, 1985) (Figures 3-7 and 3-8). Shoreface parasequences of the Emery Sandstone Member are exposed in the Book Cliffs near Price, Utah (Figure 3-8). Sandstone deposits are separated by offshore shales of the Blue Gate Shale Member of the Mancos Shale and are laterally continuous in outcrop (Figure 3-7). The Book Cliffs is an excellent location to study reservoir

continuity since the outcrops display both large scale and smaller, interwell-scale heterogeneities.

Two study areas were chosen to assess the cement distribution within the Emery Sandstone Member. Shoreface parasequences were observed in continuous exposures in Garley Canyon and Carbonville, Utah (Figure 3-7). Garley Canyon is a 20 m high cliff face that exposes three shoreface parasequences along 800 m of depositional-strike that contains the complete stratigraphic succession. The upper-most parasequence is the focus of this study (Figure 3-9). The Carbonville exposure provides cross-sectional views of a locally-cemented shoreface deposit in both the strike and dip orientations, providing a three-dimensional view of the stratigraphic architecture and interwell-scale heterogeneity. Two parasequences are exposed along a 700 m depositional-strike section at Carbonville (Figure 3-10). The upper-most parasequence along the strike section is the focus of the study and is 15 m thick. Carbonville also provides cross-sectional plan views of calcite concretions, as they are commonly exposed on the flat cliff top, further enhancing the three-dimensional dataset of concretion morphology.

The studied parasequences contain facies representing offshore, offshore-transition zone and lower shoreface deposits and show an upward increase in the proportion of sandstone beds. Calcite cements are locally distributed within the outcrops, as

tabular-shaped concretions that generally follow the bedding planes of the shoreface deposits.

### **3.3.2 Facies**

#### ***Bioturbated muddy siltstone***

This facies is a grey, organic-rich bioturbated muddy siltstone that occurs at the base of the parasequence, overlying the flooding surface (Figure 3-11a). It is interpreted as an offshore deposit and represents the Blue Gate Member of the Mancos Shale at the study locations.

#### ***Bioturbated siltstone***

This facies is a bioturbated siltstone that is inter-bedded with hummocky cross-stratified sandstones (Figure 3-11b). It is interpreted as a fairweather deposit that was deposited between storm events in the offshore-transition zone.

#### ***HCS sandstone***

This facies consists of sandstone beds that contain hummocky cross-stratification (Figure 3-11c). The sandstone beds are commonly amalgamated and represent storm deposition above fairweather wave base, as little or no fine-grained sediment is deposited between the storm events. It is interpreted as a storm event bed in the

lower shoreface, more precisely the proximal lower shoreface as it is commonly amalgamated.

### **3.3.3 Dimensions, Geometry and Distribution of Calcite Concretions**

Calcite concretions were observed at both outcrop locations in this study and were exposed as orange, tabular lense-shaped bodies within the host facies. Unique topographic exposures of the concretions at Carbonville show that they are circular in shape in plan view (Figure 3-12). The concretions in this study occur in the HCS sandstone beds, the highest reservoir quality facies of the exposed parasequences, and are concentrated near the flooding surfaces. The distribution of concretions roughly follows the bedding planes of the sandstone deposits and thickness is constrained by the thickness of the host sandstone bed. The concretions are confined within the hummocks of the sandstone beds.

Calcite concretions occur in the HCS sandstone beds in both the lower shoreface and offshore-transition zone deposits in the studied sections at Garley Canyon and Carbonville. At Garley Canyon, they are present dominantly in the amalgamated HCS sandstones in the lower shoreface deposits (76% of the total concretions) and at Carbonville, they are dominantly present within the non-amalgamated HCS sandstone beds of the heterolithic offshore-transition zone deposits (63% of the total concretions).

The maximum observed length of all large-scale concretions was measured from the outcrop photomosaics. At Garley Canyon, apparent length and thickness of 121 concretions were measured in the 800 m depositional-strike section (Figure 3-13). The concretions range from 0.9-14.2 m in length, 0.4-3.4 m in thickness and 0.5-40.3 m<sup>2</sup> in area (Figure 3-14a-c). Median dimensions of the concretions are 3.7 m in length, 1.2 m in thickness and 4.2 m<sup>2</sup> in area. At Carbonville, apparent length and thickness of 190 concretions were measured in the 700 m depositional-strike section (Figure 3-15). The concretions range from 1.3-19.6 m in length, 0.4-5 m in thickness and 0.5-65.3 m<sup>2</sup> in area (Figure 3-16a-c). Median dimensions of the concretions are 4.6 m in length, 1.3 m in thickness and 6.1 m<sup>2</sup> in area.

McBride *et al.* (1995) characterize concretions as elongate if the aspect ratio (length/thickness) of the concretion is greater than 2.5:1 and equant if less than 1.5:1. Those that fall between those ratios are classified as subequant. Based on this definition, most of the concretions in this study are elongate (Figure 3-17a and b). The median aspect ratio of the observed concretions is 2.93 at Garley Canyon and 3.67 at Carbonville). At Garley Canyon, 67% of the concretions are elongate and 32% are subequant. 74% of the concretions at Carbonville are elongate, while 18% are subequant. By McBride's (1995) definition, rare occurrences of equant concretions were observed in the study.

Of the area exposed in Garley Canyon, 9% of the section is cemented, with concretions making up 19% and 3% of the area of the lower shoreface and offshore-transition zone deposits, respectively. At Carbonville, 11% of the area exposed in the strike section is cemented, with 9% and 12% of the area in the lower shoreface and offshore-transition zone deposits, respectively, containing concretions.

At both locations, the vertical cemented fraction of the sections has a bimodal distribution, reflecting the distribution of concretions within the HCS sandstone beds of the lower shoreface and offshore-transition zone deposits within the parasequences (Figure 3-18a and b). Cement abundance is highest along the boundary between the offshore-transition zone and lower shoreface deposits. The vertical distribution varies, however, at both locations, with the highest cemented fraction occurring in the lower shoreface deposits at Garley Canyon and in the offshore-transition zone deposits at Carbonville. At Garley Canyon, cement abundance is highest in the lower shoreface deposit and the highest cemented fraction occurs in the lower half of this deposit at the boundary with the underlying offshore-transition zone deposit. Within the offshore-transition zone deposit, the cemented fraction is lower than that in the overlying deposit, but there is an increase in cement abundance in the upper half of this zone. At Carbonville, the cement abundance is highest in the offshore-transition zone deposit. The cemented fraction increases toward the top of this zone with the highest proportion of concretions occurring at the boundary between this deposit and the overlying lower shoreface deposit, which displays a decrease in

cementation. Within the lower shoreface deposit, the vertical variation is fairly uniform, with a slight increase toward the top of the section.

The horizontal distribution of concretions throughout the outcrops can be described by plotting the concretion centers. Figure 3-19a and b show that the concretions tend to be randomly distributed across the studied sections. At Carbonville, there is a somewhat bimodal distribution that shows a higher distribution of concretions in the first half of the outcrop (Figure 3-19b). This reflects the decrease in the number of concretions observed in the lower shoreface deposits throughout the deposit. The distribution of concretions within the offshore-transition zone displays no apparent horizontal trend.

Concretions are exposed along the top of the outcrop at the Carbonville location, providing a plan view of the geometry and distribution of the diagenetic features (Figures 3-12 and 3-20). Some can be traced to the outcrop face and display a three-dimensional view (Figure 3-21), making this an excellent location for studying cementation in shoreface deposits. The concretions are circular in shape and have the same lateral dimensions in both the strike and dip directions (Figure 3-16). They are localized within the hummocks of the HCS sandstone beds and appear to be randomly distributed along the surface (Figure 3-20), just as they are in the exposed faces.



### **3.3.4 Variogram Models for Cement Distribution**

The outcrop maps containing the polygon traces of concretion outlines and boundary surfaces were transformed to cornerpoint grids of concretion indicators for both outcrop sections. Simple grids were constructed in the Petrel E&P Software Platform along the lengths of the georeferenced sections (x direction) with cell dimensions of 0.5 m in the x direction and 1 m in the y direction. The grid was limited to one cell in the y direction.

Polygons were digitized along the top of the outcrop, the boundary between the lower shoreface and offshore-transition zones, and the base of the offshore-transition zone and used to mark the limits of the grid and reservoir zones in the gridding process. The reservoir zones within the lower shoreface and offshore-transition zones were layered with 10 cm thick cells in the z direction. The resultant grid in the reservoir interval has cell dimensions of 0.5 m x 1 m x 0.1 m to capture the distribution of cement. In the horizontal and vertical directions, the grid sizes are 1560 by 100 cells and 1300 by 148 cells for the Garley Canyon and Carbonville sections, respectively.

Cement was transformed to an indicator variable and cemented rock was assigned a value of 1 and uncemented rock was assigned a value of 0. Grid cells that are contained within the concretion outlines where cementation occurs were set to 1. Indicator variograms were calculated from the populated grid to describe the spatial

continuity of the concretions in the horizontal and vertical directions and can be applied to field analogue reservoir models.

At Garley Canyon, the variance was modelled using an exponential variogram in the horizontal direction and a spherical variogram in the vertical direction (Figure 3-22). It has a variance of 0.94 and the vertical variogram does not reach the total variance due to zonal anisotropy, indicating the presence of an areal trend. There is a slight oscillation in the horizontal variogram due to cyclicity in cement occurrence and is not considered significant. It has a horizontal range of 6.5 m and vertical range of 1.2 m, with a horizontal to vertical range ratio of 5:1.

At Carbonville, the variance was modelled using an experimental variogram and has a variance of 0.93 (Figure 3-23). The horizontal variogram does not reach the total variance due to the presence of zonal anisotropy and is indicative of an areal trend. The vertical variogram has a negative correlation at large ranges whereby it continues to increase above the sill and is indicative of a vertical trend. It has a horizontal range of 7.7 m and a vertical range of 1.8 m, with a horizontal to vertical range ratio of 4:1.

### **3.4 HEBRON ASSET RESERVOIR MODEL**

Using a hierarchical approach, a 3D reservoir model of the Ben Nevis Formation at the Hebron Asset was constructed using geophysical, geological and petrophysical

data and integrated sedimentological interpretations from a detailed core study and geostatistical data from an outcrop analogue in the Book Cliffs, Utah. The model was constructed in the Petrel E&P Software platform and conditioned to Hebron well data to generate a grid with populated facies and petrophysical models that are representative of the reservoir volume (Figure 3-24).

A seismic interpretation of the top and base reservoir horizons and faults were used to generate a structural model for the reservoir succession (Figure 3-25). The Ben Nevis and mid-Aptian Unconformity horizons define the upper and lower limit of the grid that is further divided into stratigraphic zones that are marked by correlatable flooding surfaces (Figures 3-25 and 3-26). Sixteen conformable zones were interpreted at each well and correlated throughout the reservoir to constrain the statistical analysis and distribution of facies data (Figure 3-26). The layering scheme of the grid was particular to each zone and defined by facies variability to ensure that the model reflects the heterogeneous reservoir distribution and its impact on fluid flow (Table 3-2).

#### **3.4.1 Facies Model**

Facies classification was based on an analysis of core and log data. A detailed sedimentological study of core obtained from six wells in the Hebron Asset identified sedimentary facies that are representative of lower shoreface and offshore-transition zone depositional environments within a wave-dominated shoreface (described in

Chapter 2) (Figure 3-27). The sedimentologically defined facies were related to petrophysical log data and grouped into five facies for the purposes of reservoir modelling to guide the distribution of reservoir and flow properties (as described above) (Table 3-1 and Figure 3-5). A cross-plot of porosity and  $V_{\text{shale}}$  according to the sedimentary facies described in core illustrate that the facies form clearly defined fields based on the petrophysical properties and form the basis for the definition of the modelled facies types (Figure 3-28). The modelled facies were defined as follows:

Laminated sand - porosity greater than 18%

Bioturbated sand - porosity between 8-18% and  $V_{\text{shale}}$  less than 22%

Bioturbated silt - porosity less than 18% and  $V_{\text{shale}}$  greater than 22%

Calcite - porosity less than 8% and  $V_{\text{shale}}$  less than 22%

Shale - porosity less than 10% and  $V_{\text{shale}}$  greater than 40%

The facies model (Figure 3-29) was stochastically populated using the sequential indicator simulation (SIS) algorithm based on the statistical distributions of the facies within each of the sixteen stratigraphic zones, conditioned to the well data and guided by the conceptual depositional model (Figure 3-27). The facies model represents a transgressive succession of prograding parasequence sets that are defined by the model zones, as indicated by the log and core data in the Ben Nevis Formation (Figure 3-29) (See Appendix D). Statistical analyses of the facies generated proportion histograms, vertical proportion curves, and variogram models

for each facies by zone and were used in the facies modelling process to ensure that the model honoured the well data and was an accurate representation.

Global facies proportions for the seven wells in this study are 37% laminated sand, 24% bioturbated sand, 8% calcite, 26% bioturbated silt, and 5% shale (Figure 3-30). Facies proportions were calculated by zone and any facies, with the exception of calcite, with proportions less than 4% were identified as candidates for amalgamation with a similar facies due to the difficulty of determining appropriate histograms and variograms for such few data (Table 3-3). Areal facies variability is present throughout the Hebron Asset and facies proportion maps, guided by well control and the conceptual understanding of the shoreface depositional model, were generated to further guide the stochastic population of facies in the modelled volume (Figure 3-31). The vertical proportions of facies were analyzed on a zone-by-zone basis and vertical proportion curves were generated to capture the vertical variations in facies throughout each zone in the stochastic model.

The spatial distribution of the facies was determined by the calculated variograms. Vertical variograms were calculated with lag spacings of 0.1 m, the typical vertical sampling interval of data (See Appendix C). Vertical variograms are valid up to about a half of the zone thickness and determines the number of lags to use in the calculation of the vertical variogram in each zone. A tolerance angle of 45° and a lag tolerance of 50% of the lag spacing were used in the variogram calculations. The

vertical variograms are well-defined due to the large quantity of data available vertically along the well and vertical facies ranges were calculated for each zone (Table 3-4).

Horizontal variograms could not be calculated from the well data because the quantity of data was insufficient due to the large well spacing in the reservoir. The well-defined vertical variogram models were used to calculate the horizontal variograms, by using horizontal-to-vertical (H:V) anisotropy ratios. Reservoirs of this type typically display H:V ratios of 100:1 and this was used to calculate the horizontal ranges in both the major and minor directions (Table 3-4), as there are too few wells to determine horizontal anisotropy. Calcite used a H:V anisotropy ratio of 5:1 that was calculated from the variogram models of concretion distribution in the exposed outcrop face at Garley Canyon, described in a preceding section.

A reliable distribution of facies is fundamental to creating a reservoir model that can accurately predict fluid flow. Reservoir properties are controlled by facies and the accuracy of their distribution relies on a predictive facies model. Improved facies models benefit from the integration of geological data with conceptual geologic models and outcrop analogue data to better constrain the distribution of facies.

#### **3.4.2 Petrophysical Model**

The distribution of petrophysical properties were constrained by the facies model and simplistically distributed in order to assess the impact that geologic heterogeneity,

alone, has on reservoir performance. Average values of porosity, permeability and water saturation were assigned by facies (Table 3-5) to create a petrophysical model that is representative of the studied reservoir and that eliminates the uncertainty created by a stochastic distribution of reservoir properties.

### **3.5 STREAMLINE FLOW SIMULATION**

Streamline flow simulation in RMSstream (in the Irap RMS modelling package) was used to demonstrate the influence that concretions have on fluid flow and reservoir performance. RMSstream is a supplementary reservoir characterization tool that moves fluids along one-dimensional streamlines rather than through three-dimensional grid blocks as in finite difference simulation (Roxar Software Solutions, 2012). As a result, streamline simulation is well suited for high-resolution models with high degrees of geologic heterogeneity as they run faster than traditional simulations. Streamlines represent the trajectory of a moving particle through porous medium as a result of pressure gradients that exist within the reservoir model. The generated streamlines provide a visualization of flow paths between a producer and injector pair and an understanding of reservoir connectivity. The distribution of streamlines reflects the geologic variability as they are dictated by variability in permeability. Streamline simulation is a powerful tool and shows how dynamic reservoir characteristics are linked to static reservoir characteristics.

To quantify the effects of concretions on flow, simulations were performed on high-resolution reservoir models that were populated with and without calcite cement. A

sector model was created in the Ben Nevis Field from the reservoir model of the Hebron Asset described above (Figure 3-32). The sector encompasses an area of approximately 1500 km<sup>2</sup> and includes the Ben Nevis L-55 well (Figure 3-33). To reflect the sizes of concretions measured in the field study, a highly-refined grid was created with dimensions in the x and y directions of 2 m x 2 m. To minimize cell count and increase computational efficiency, the grid was restricted to the stratigraphic zones 8-10 defined in the Hebron Asset reservoir model between the FSSB and Horizon 9 flooding surfaces (Figure 3-26). The layering scheme was defined by cell thicknesses of 1 m and the resultant grid contained approximately 24 million cells.

The statistical distribution of facies in the sector was described by the calculations and distribution determined in the full-field model of the Hebron Asset, which was conditioned to all 7 wells included in this study. The stochastic distribution of calcite in the high-resolution sector model (Figure 3-34a) used proportion histograms, vertical proportion curves and vertical variograms (see Appendix C) calculated from the subsurface well data in the full-field model and was conditioned to outcrop analogue data to calculate horizontal variograms using the H:V anisotropy ratio of 5:1 defined from the field study (as described in the preceding section) (Table 3-4). To compare the effects of a model with and without calcite, an alternate model was created that replaces calcite with laminated sandstone (Figure 3-34b). This is a reasonable proxy since the concretions observed in outcrop were restricted to the



storm bed deposits of the same lithology. Petrophysical properties were assigned to the model using values that are representative of each facies for porosity, permeability (Figure 3-35) and water saturation as described in the preceding chapter (Table 3-5).

Streamline simulation was used to demonstrate the impact that low permeability concretions in shoreface reservoirs have on fluid flow. The L-55 well was used as the producer and a water injector was placed 600 m down-dip from the producer. This study used a single-phase simulation with an injection rate of 1200 m<sup>3</sup>/day and a production rate of 1000 m<sup>3</sup>/day. Bottom hole pressure was constrained to 300 bar for the injector and 200 bar for the producer. The effect of concretions on fluid can be seen by comparing the breakthrough times of streamlines at the producer and monitoring the advancement of the injection fluid front.

Concretions act as baffles and create tortuous flow paths through the reservoir (Figures 3-36 - 3-40). The advancing fluid front is fingered, as fluid flow must bypass and move around the impermeable concretions. The preferential flow paths, created by the variability in the permeability distribution, result in unswept reservoir behind the concretionary bodies as the fluid front advances towards the producer.

Concretions cause the fluid front to advance faster and farther and result in earlier breakthrough at the producer (Figures 3-36 - 3-41). Breakthrough in the model with

calcite cement occurs at 704 days and is delayed by 33% in the model without calcite cement. Streamline simulation was also conducted on the same sector region in the 100 m x 100 m generated for the full-field model, as this is the normal grid size used in traditional simulations to demonstrate the effect that an overrepresentation in calcite dimensions has on reservoir performance. Lateral calcite dimensions of 100 m increased breakthrough by 24% in comparison to calcite dimensions of 2 m x 2 m.

### **3.6 CONCLUSIONS**

In hydrocarbon reservoirs, fluid flow is controlled by the distribution of facies and diagenetic cements and incorporating various scales of heterogeneity is critical for an accurate prediction of flow behaviour and reservoir performance. Incorporating calcite cements in a logical manner is a significant challenge in reservoir modelling, as it is notoriously difficult to quantify their distribution and architecture in the subsurface. Outcrop studies aid reservoir modelling in numerous ways by providing a conceptual understanding and a quantification of the spatial distribution of facies and reservoir heterogeneity.

The Ben Nevis Formation at the Hebron Asset consists of a transgressive sequence of stacked shoreface parasequences. A more shoreline-distal depositional setting is reflected by the heterolithic nature of the succession, where there is a high preservation of bioturbated and fine-grained fairweather facies that are inter-bedded with high quality HCS storm deposits. The variability in petrophysical properties

caused by the heterogeneous distribution of facies of contrasting reservoir qualities is further enhanced by the precipitation of calcite cement within the highly-porous shoreface sandstones of the Ben Nevis Formation. An abundant amount of diagenetic cement is recognized in both core and petrophysical well log data. Based on this data alone, it is difficult to infer the lateral dimensions and spatial distribution of calcite concretions throughout the reservoir.

Shoreface deposits in outcrop analogues in Garley Canyon and Carbonville are diagenetically altered by the precipitation of calcite concretions. The concretions are tabular and roughly follow the bedding planes of the HCS sandstone beds, the highest reservoir quality facies in both the lower shoreface and offshore-transition deposits. The concretions appear to be randomly distributed along the outcrop and are localized within the hummocks of the HCS sandstone beds. About 10% of the exposed parasequences are cemented and cement abundance is highest along the boundary between the lower shoreface and offshore-transition zone deposits.

Quantitative outcrop data from the calcite-cemented shoreface parasequences in the Book Cliffs provide geostatistical descriptions of concretion distributions to model the spatial correlation of calcite in the Ben Nevis Formation at the Hebron Asset. Indicator variograms model the spatial distribution of concretions in outcrop and supplement the vertical proportion trends and distribution of calcite determined from well data. H:V anisotropy ratios of 5:1 and 4:1 were calculated from the modelled

variance of concretion distribution for Garley Canyon and Carbonville, respectively. A H:V anisotropy ratio of 5:1 was applied to the well-defined vertical variograms in the Hebron reservoir model and conditioned to well data to model calcite cement using the SIS algorithm. Plan view exposures of the concretion along the top of the outcrop indicate that they are circular in shape and therefore, isotropic in both the major and minor depositional directions.

Streamline simulation indicates that the presence of concretions in siliciclastic shoreface reservoirs impact fluid flow behaviour. Concretions cause flow paths to be more tortuous and result in unswept reservoir areas and earlier breakthrough. Breakthrough was 33% faster in the cemented-reservoir model of the Ben Nevis Formation at the Hebron Asset, illustrating the importance of realistically modelling the distribution of cements in reservoirs to accurately predict fluid flow.

**Table 3-1.** Sedimentary and ichnological description of the reservoir facies observed in the core study of 6 wells that penetrated the Ben Nevis Formation in the Hebron Asset and their associated depositional environment.

Facies	Characteristics	Bioturbation	Bedding Thicknesses	Depositional Environment
<b>Bioturbated silty mudstone</b>	Mudstone, siltstone, intensely bioturbated (BI 60-90%). Internal depositional structures not preserved. Commonly caps small-scale fining-upwards successions.	<i>Ophiomorpha</i> , <i>Phycosiphon</i> , <i>Teichichnus</i> and <i>Asterosoma</i>	Bedsets up to 1 m thick	Fairweather deposit in Offshore- Transition Zone
<b>Bioturbated Sandstone</b>	fgL to vfgU sandstone, siltstone, highly bioturbated (BI 60-70%). Component of carbonaceous debris. Internal depositional structures not preserved. Bioclastic components are present (fragments of serpulid worm tubes and oyster shell debris).	<i>Ophiomorpha</i> , <i>Planolites</i> , <i>Teichichnus</i> , and <i>Phycosiphon</i>	Beds are under 1 m thick	Fairweather deposit in Lower Shoreface.
<b>Bioclastic Sandstone</b>	Matrix supported (fg sandstone) lag deposited on scoured surface. Massive in appearance with no bedding features. Lag consists of bioclastic components (fragments of serpulid worm tubes, bivalves and gastropods). Sometimes cemented with diagenetic calcite.	N/A	Beds are up to 3 m thick	Storm deposit in Proximal Lower Shoreface
<b>Laminated Sandstone</b>	fgL to vfgU sandstone, well sorted, with parallel to low angle lamination. Ripples or ripple cross-bedding may be observed at the tops of beds. Clay drapes and carbonaceous are commonly deposited along laminae. Lag deposits of sideritized mudstone rip-up clasts are common along basal scour contacts. Commonly overlies and is associated with bioclastic sandstone facies.	N/A	Bed thicknesses range from a few cm to m-scale thicknesses	Storm deposit in Distal Lower Shoreface (amalgamated beds) to Offshore-Transition Zone (interbedded with fairweather deposits)

**Table 3-2.** Grid size and layering scheme of the Hebron Asset reservoir model.

X and Y cell dimensions: 100 m x 100m		
Total Cells: 159 x 91 x 1324		19.2 million
Zone	Cell thickness	Layers
1	1.1	63
2	0.82	61
3	0.81	76
4	0.66	68
5	0.41	171
6	0.65	86
7	0.9	35
8	0.8	65
9	0.75	85
10	1.02	64
11	0.9	183
12	1.81	43
13	0.86	84
14	0.46	181
15	2.42	17
16	1.71	42

**Table 3-3.** Facies proportions by percentage (%) for each of the sixteen stratigraphic zones within the Hebron Asset reservoir model. Highlighted facies were amalgamated to improve the statistical analysis and the resultant proportions are provided.

Zone	Laminated Sand	Bioturbated Sand	Calcite	Bioturbated Silt	Shale
1	3.7 (0)	20.3 (24.0)	4.2	45.6	26.2
2	9.9	13.5	3.0	61.2	12.3
3	22.4	18.8	7.0	49.3 (51.8)	2.5 (0)
4	23.9	31.7	5.7	37.3 (38.7)	1.4 (0)
5	20.7	24.9	6.2	44.3 (48.2)	3.9 (0)
6	49.6	22.7	3.1	22.8 (4.6)	1.8 (0)
7	39.5	23.1	7.5	26.1 (29.9)	3.8 (0)
8	45.6	32.4	9.8	11.2 (12.2)	1.0 (0)
9	50.2	32.8	5.7	10.6 (11.2)	0.6 (0)
10	42.6	27.7	5.0	24.7	0
11	39.4	24.2	24.7	11.3 (11.7)	0.4 (0)
12	48.4	24.2	12.5	11.0 (14.9)	3.9 (0)
13	54.9	25.3	9.1	10.2 (10.7)	0.5 (0)
14	46.8	31.5	12.4	9.3 (9.4)	0.1 (0)
15	50.1	27.1 (31.1)	18.8	4.0 (0)	0
16	63.0	16.3 (20.4)	16.6	4.1 (0)	0

**Table 3-4.** Calculated variogram settings for each reservoir facies on a by-zone basis in the Hebron Asset reservoir model. The variograms are used as statistical input for the stochastic population of the facies model using the sequential indicator simulation (SIS) algorithm. Horizontal variogram ranges are calculated from the well-defined vertical variograms by using a H:V anisotropy ratio of 100:1 for the depositional facies and a ratio of 5:1 for calcite.

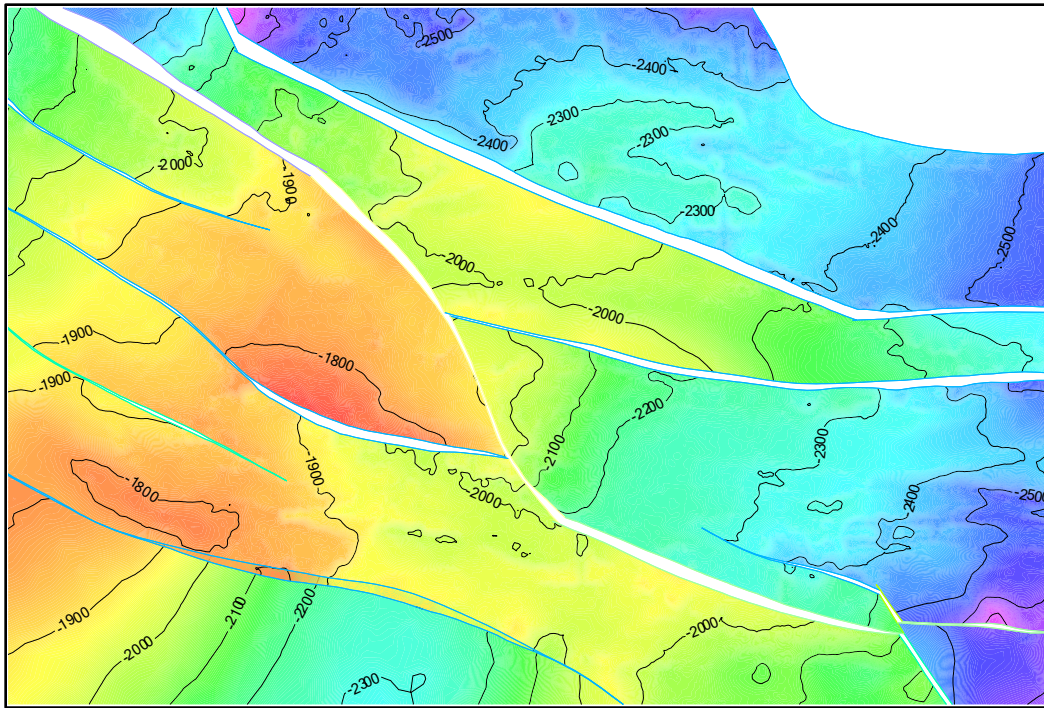
Zone	Facies	Type	Sill	V Range	H Range	Zone	Facies	Type	Sill	V Range	H Range
1	Laminated Sand	N/A	N/A	N/A	N/A	2	Laminated Sand	Exponential	0.91	2.64	264
	Bioturbated Sand	Exponential	0.97	1.51	151		Bioturbated Sand	Exponential	1.04	1.08	108
	Calcite	Exponential	1.18	1.10	5.5		Calcite	Exponential	1.24	0.82	4.1
	Bioturbated Silt	Exponential	1.00	1.87	187		Bioturbated Silt	Exponential	1.03	1.73	173
	Shale	Exponential	0.54	4.94	494		Shale	Exponential	0.70	7.89	789
3	Laminated Sand	Spherical	0.58	1.61	161	4	Laminated Sand	Exponential	1.17	2.94	294
	Bioturbated Sand	Exponential	1.16	3.81	381		Bioturbated Sand	Exponential	0.90	1.85	185
	Calcite	Exponential	0.94	1.68	8.4		Calcite	Exponential	0.90	1.31	6.5
	Bioturbated Silt	Exponential	1.31	3.27	327		Bioturbated Silt	Exponential	1.14	2.25	225
	Shale	N/A	N/A	N/A	N/A		Shale	N/A	N/A	N/A	N/A
5	Laminated Sand	Exponential	1.00	1.41	141	6	Laminated Sand	Exponential	0.80	1.16	116
	Bioturbated Sand	Exponential	1.00	0.82	82		Bioturbated Sand	Exponential	1.00	1.08	108
	Calcite	Exponential	1.14	1.35	6.7		Calcite	Exponential	0.74	0.65	3.2
	Bioturbated Silt	Exponential	0.79	1.36	136		Bioturbated Silt	Exponential	0.60	1.42	142
	Shale	N/A	N/A	N/A	N/A		Shale	N/A	N/A	N/A	N/A
7	Laminated Sand	Exponential	1.00	0.90	90	8	Laminated Sand	Exponential	0.96	1.06	106
	Bioturbated Sand	Exponential	1.09	0.41	41		Bioturbated Sand	Exponential	1.15	1.57	157
	Calcite	Exponential	1.45	1.78	8.9		Calcite	Exponential	1.16	1.60	8.0
	Bioturbated Silt	Exponential	0.30	2.25	225		Bioturbated Silt	Exponential	0.95	3.19	319
	Shale	N/A	N/A	N/A	N/A		Shale	N/A	N/A	N/A	N/A
9	Laminated Sand	Exponential	0.72	1.62	162	10	Laminated Sand	Exponential	0.79	1.65	165
	Bioturbated Sand	Exponential	0.57	1.30	130		Bioturbated Sand	Exponential	0.78	1.02	102
	Calcite	Exponential	0.68	1.49	7.4		Calcite	Exponential	0.69	2.07	10.3
	Bioturbated Silt	Exponential	1.00	1.13	113		Bioturbated Silt	Exponential	0.74	1.79	179
	Shale	N/A	N/A	N/A	N/A		Shale	N/A	N/A	N/A	N/A
11	Laminated Sand	Exponential	1.33	1.74	174	12	Laminated Sand	Exponential	0.78	7.77	777
	Bioturbated Sand	Exponential	1.06	2.06	206		Bioturbated Sand	Exponential	0.86	2.01	201
	Calcite	Exponential	1.00	0.77	3.9		Calcite	Exponential	1.00	3.62	18.1
	Bioturbated Silt	Exponential	1.14	3.08	308		Bioturbated Silt	Exponential	0.91	3.49	349
	Shale	N/A	N/A	N/A	N/A		Shale	N/A	N/A	N/A	N/A
13	Laminated Sand	Exponential	0.79	2.39	239	14	Laminated Sand	Exponential	0.95	1.51	151
	Bioturbated Sand	Exponential	0.66	1.31	131		Bioturbated Sand	Exponential	0.80	1.30	130
	Calcite	Exponential	0.71	1.72	8.6		Calcite	Exponential	1.05	0.92	4.6
	Bioturbated Silt	Exponential	0.84	1.98	198		Bioturbated Silt	Exponential	0.85	1.61	161
	Shale	N/A	N/A	N/A	N/A		Shale	N/A	N/A	N/A	N/A
15	Laminated Sand	Exponential	1.00	6.26	626	16	Laminated Sand	Exponential	1.00	2.74	274
	Bioturbated Sand	Exponential	0.55	1.46	146		Bioturbated Sand	Exponential	1.00	1.02	102
	Calcite	Exponential	1.19	4.83	24.2		Calcite	Exponential	1.17	3.41	17.1
	Bioturbated Silt	N/A	N/A	N/A	N/A		Bioturbated Silt	N/A	N/A	N/A	N/A
	Shale	N/A	N/A	N/A	N/A		Shale	N/A	N/A	N/A	N/A

**Table 3-5.** Petrophysical reservoir properties assigned by facies in the Hebron Asset reservoir model for use in streamline simulation to assess the impact of calcite cement on fluid flow.

Facies	Porosity (%)	Permeability (mD)	Water Saturation (%)
Laminated sand	22	250	10
Bioturbated sand	14	60	18
Calcite	3	0.1	90
Bioturbated silt	10	3	45
Shale	8	1	80







**Figure 3-2.** Depth-structure map of the Hebron Asset of the top of the Ben Nevis Formation with the locations of the seven wells included in this study.

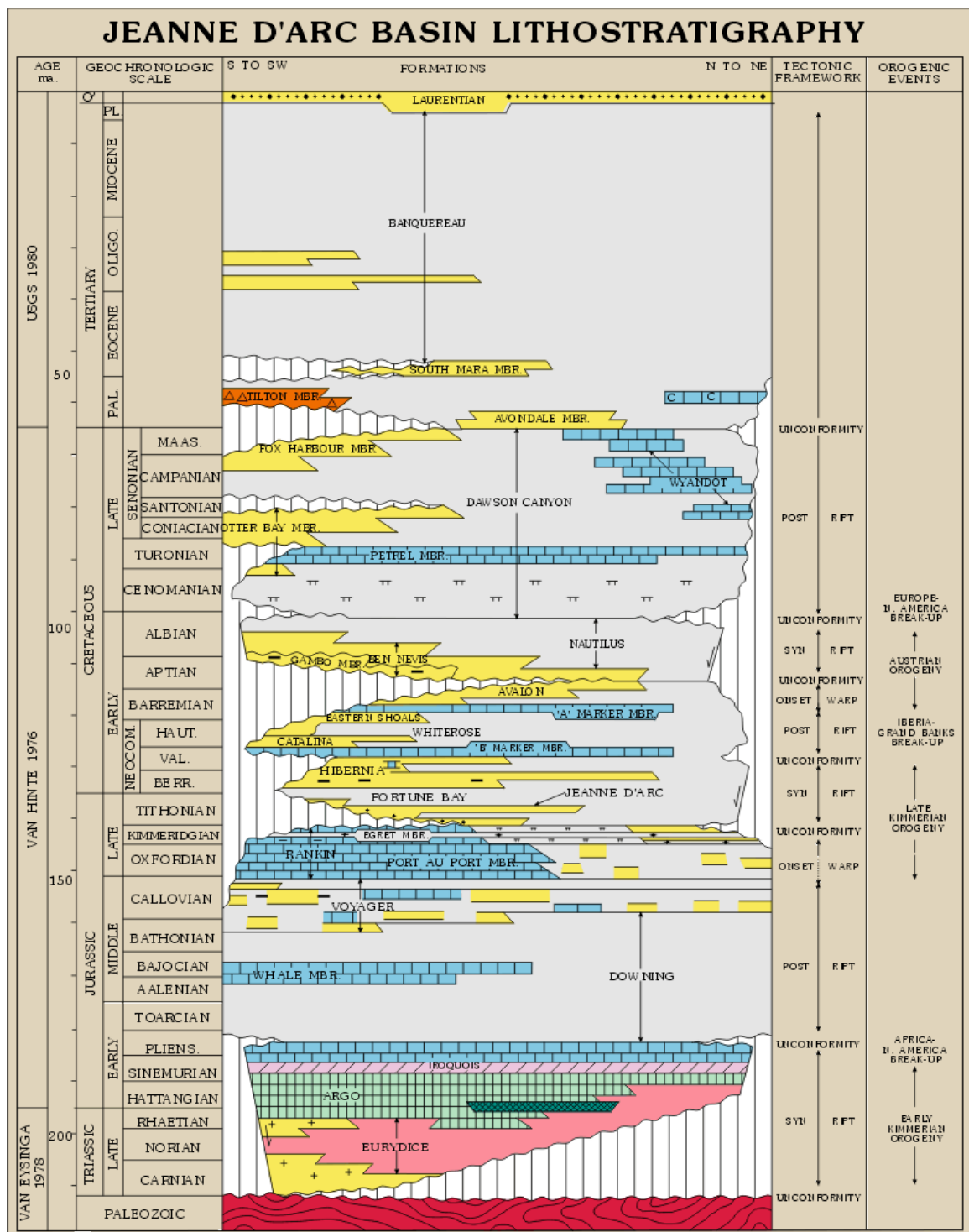
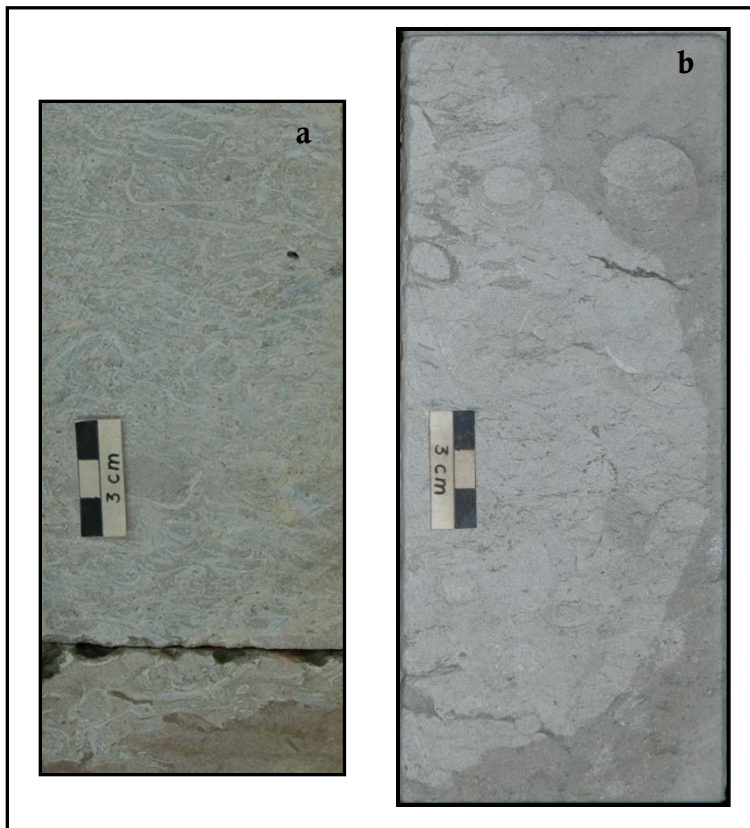


Figure 3-3. Lithostratigraphic chart of the Jeanne d'Arc Basin.



**Figure 3-4.** Calcite cement observed in core from the Ben Nevis Formation in Ben Nevis L-55. **(a)** Calcite concentrated within coquinid shell bed deposits. **(b)** Rounded and irregular nodular boundaries cross-cut the host facies.

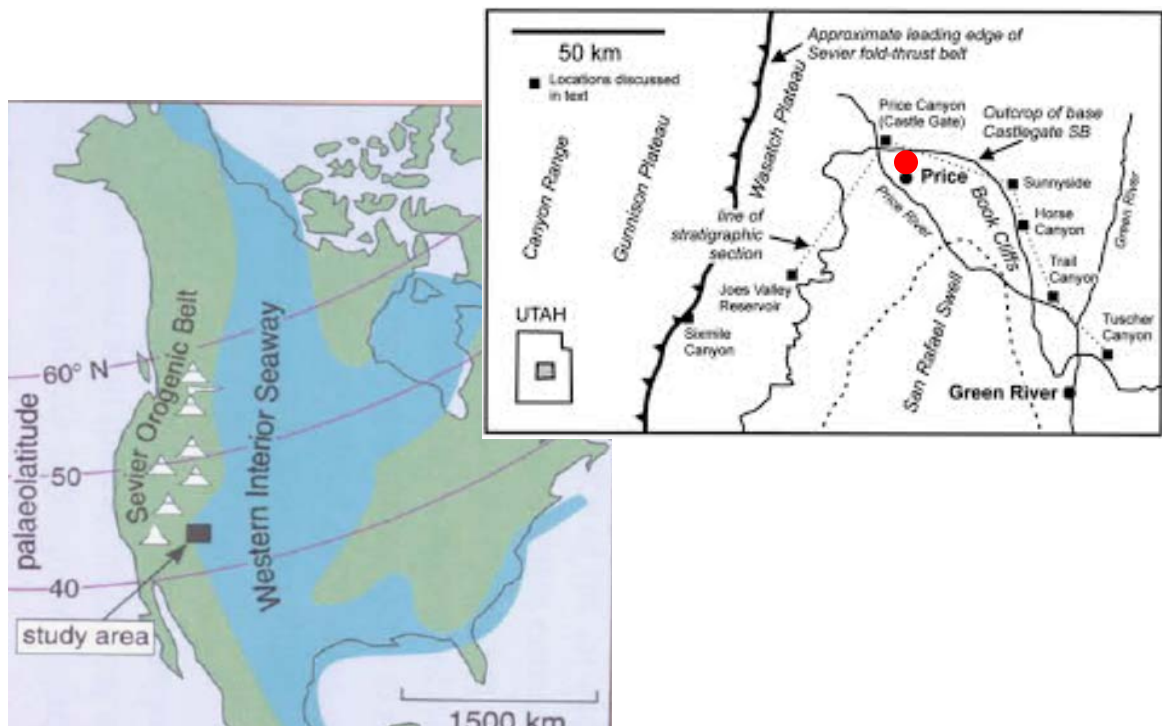


**Figure 3-5.** Reservoir facies observed and described in a core study of 6 wells that penetrated the Hebron Asset: (a) bioturbated silty mudstone; (b) bioturbated sandstone; (c) bioclastic sandstone; and (d) laminated sandstone. Facies were classified as either fairweather or storm deposits within a wave-dominated shoreface environment.

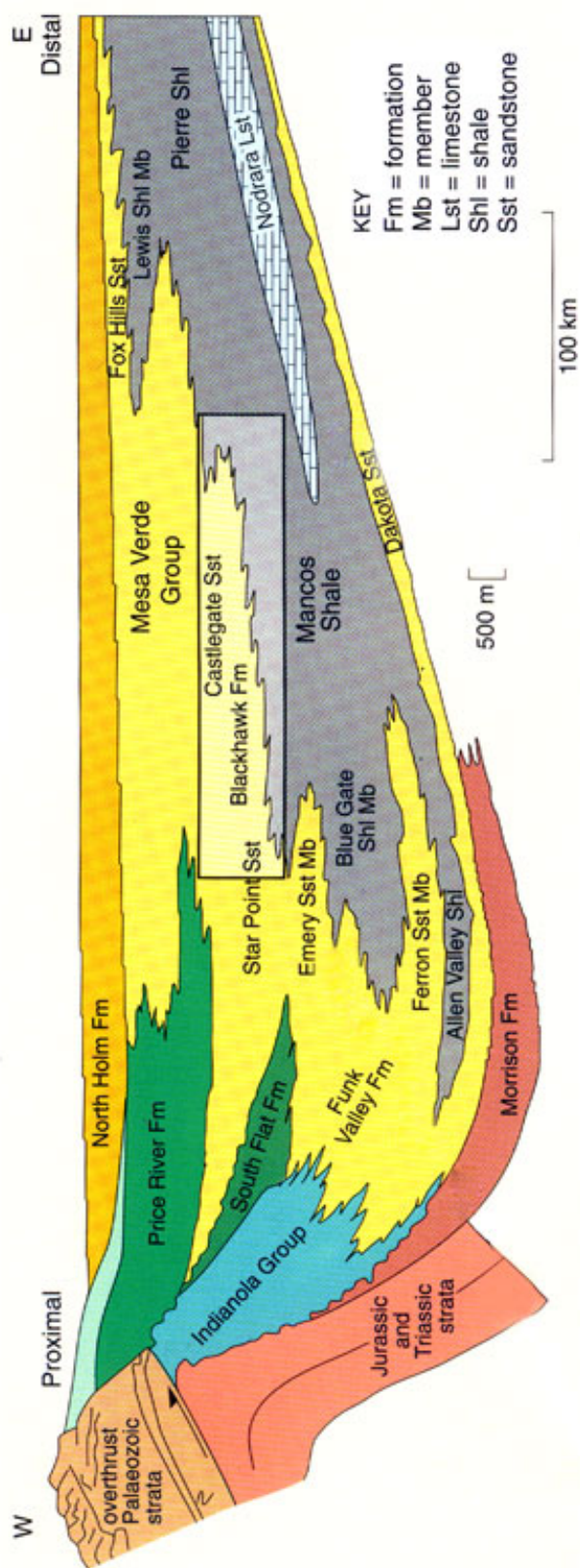




**Figure 3-6.** Calcite concretions exposed in outcrop in the Book Cliffs, Utah. The oxidation of iron within the concretions produces an orange colour, making them clearly visible and distinguishable from the uncemented host rock.



**Figure 3-7.** Location of the Book Cliffs in the Western Interior Basin in Utah (from Howell and Flint, 2003). Field study areas included two outcrops exposed near Price, Utah in Carbonville and Garley Canyon.



**Figure 3-8.** Lithostratigraphy of the Western Interior Basin in Utah (from Howell and Flint, 2003). The Emery Sandstone Member is the focus of this field study and is exposed in the Garley Canyon and Carbonville outcrops.

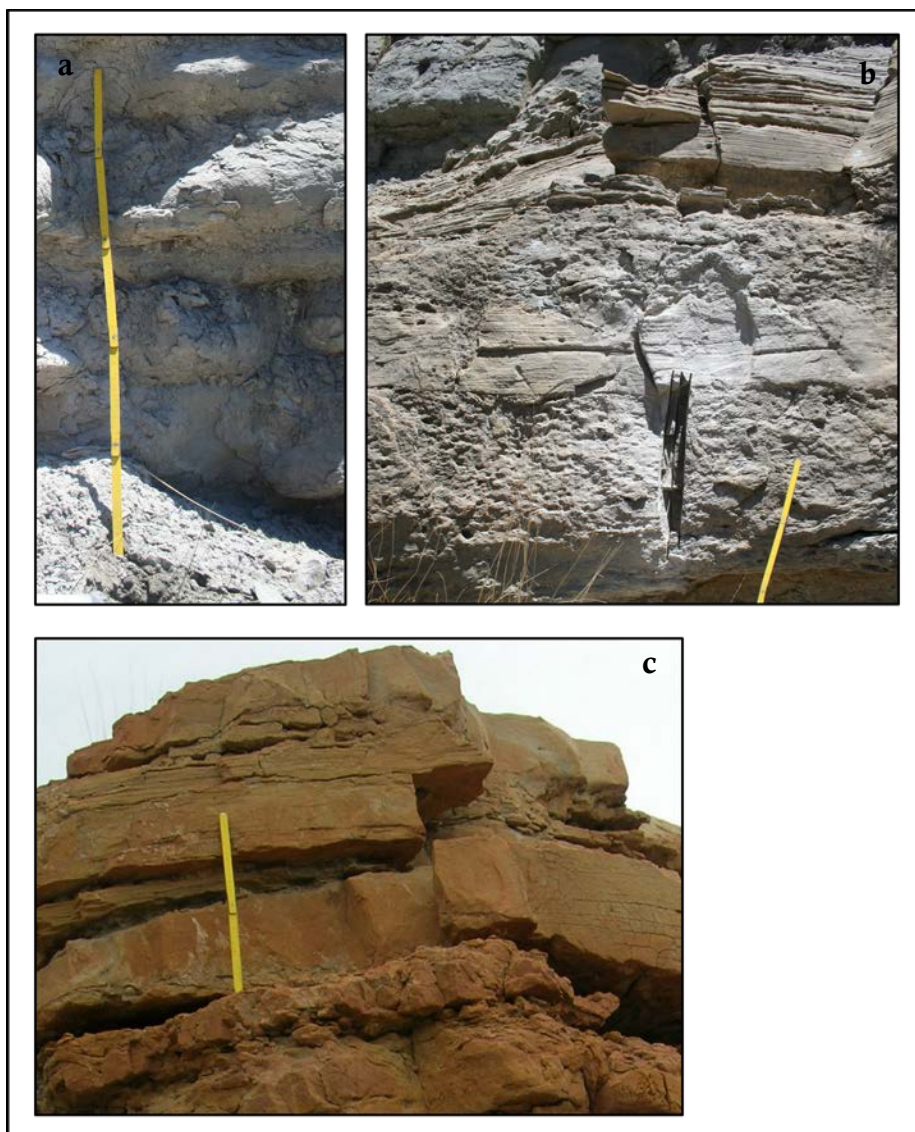


**Figure 3-9.** Exposed outcrop section in Garley Canyon, near Price, Utah.



**Figure 3-10.** Exposed outcrop section in Carbonville, near Price, Utah.



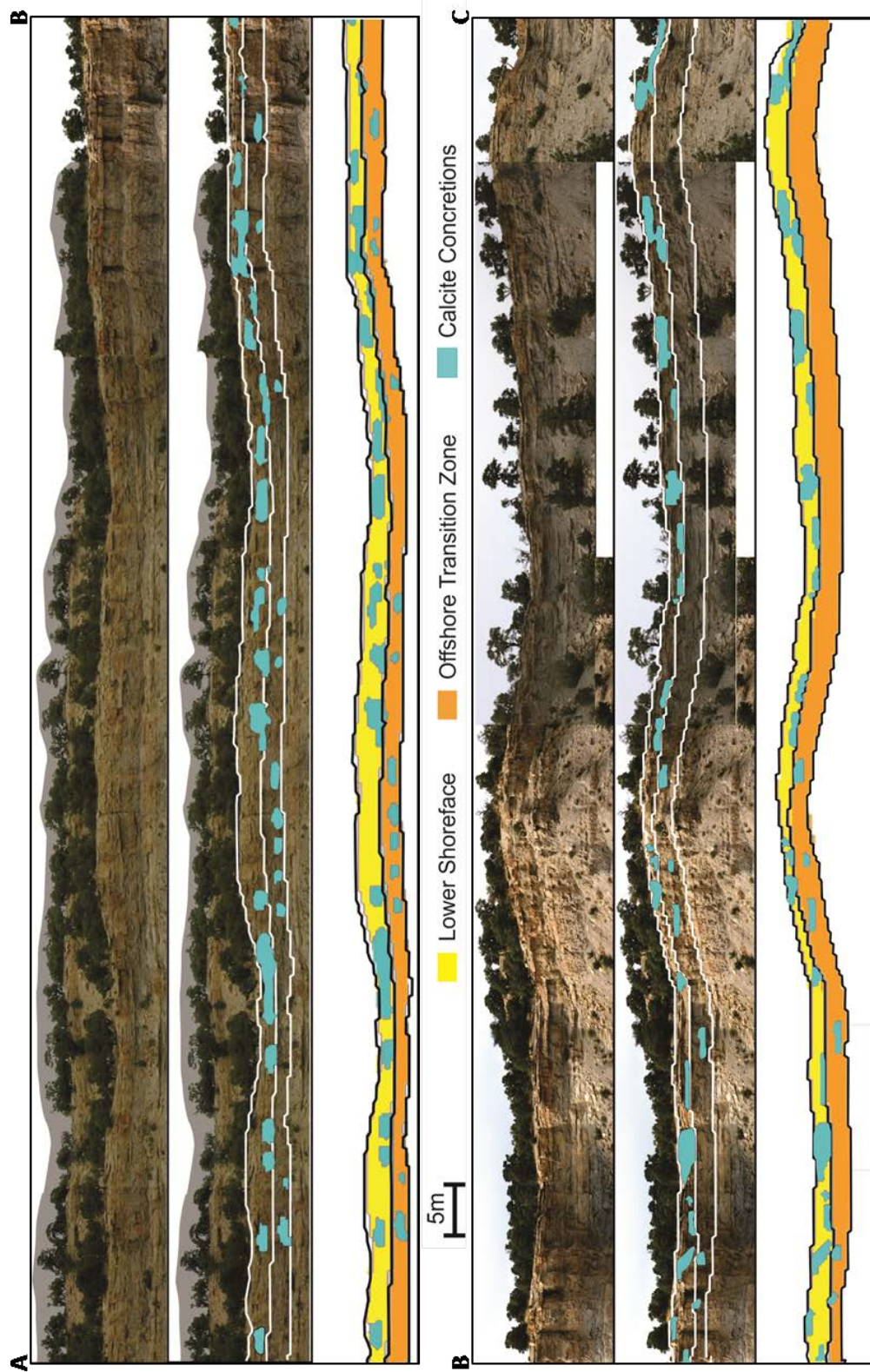


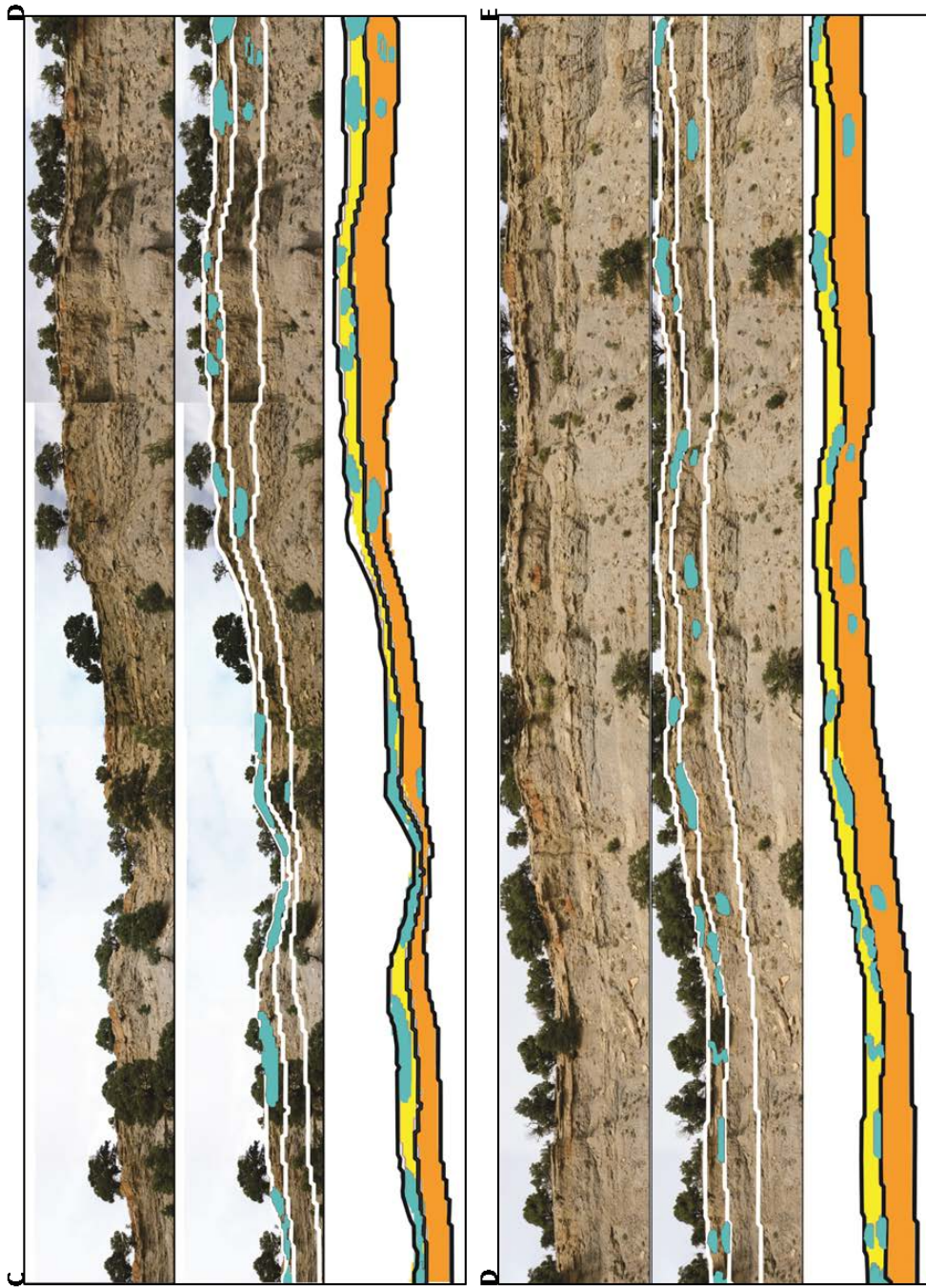
**Figure 3-11.** Facies observed in the studied outcrops in the field study: (a) bioturbated muddy siltstone; (b) bioturbated siltstone; and (c) HCS sandstone.



**Figure 3-12.** Plan view exposure of a calcite concretion along the top of the outcrop at the Carbonville study area. Concretions exposed at the surface demonstrate a circular shape.

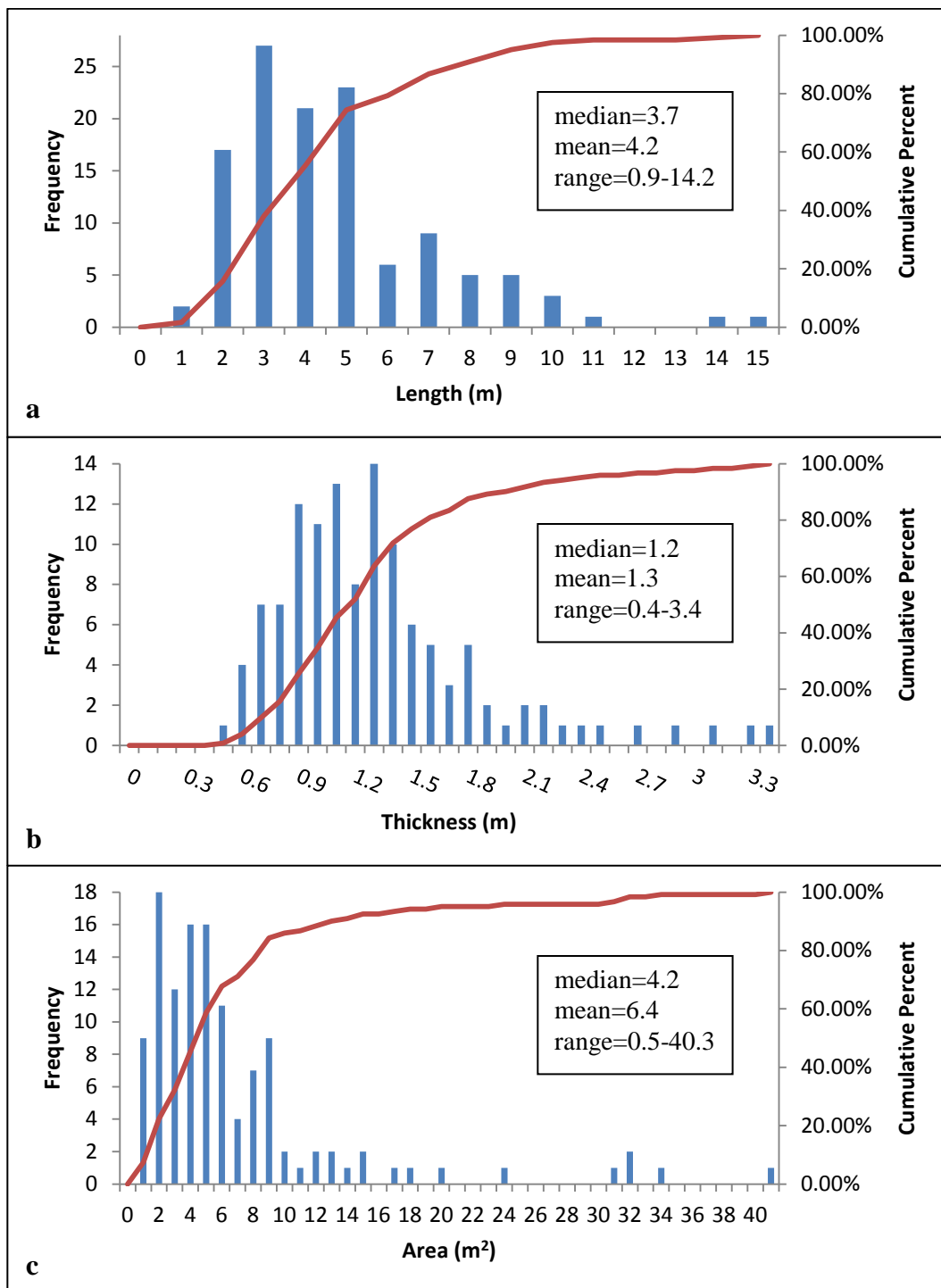






**Figure 3-13.** Facies and concretion distribution in a shoreface parasequence along the 800 m exposed outcrop face at Garley Canyon. (a) Photomosaic of the outcrop section that was used to measure the dimensions and distribution of concretions. (b) The concretions were outlined and the top and base of the studied parasequence and boundary between the lower shoreface and offshore transition zone were traced along the section as input for the (c) modelled reservoir grid of the outcrop.

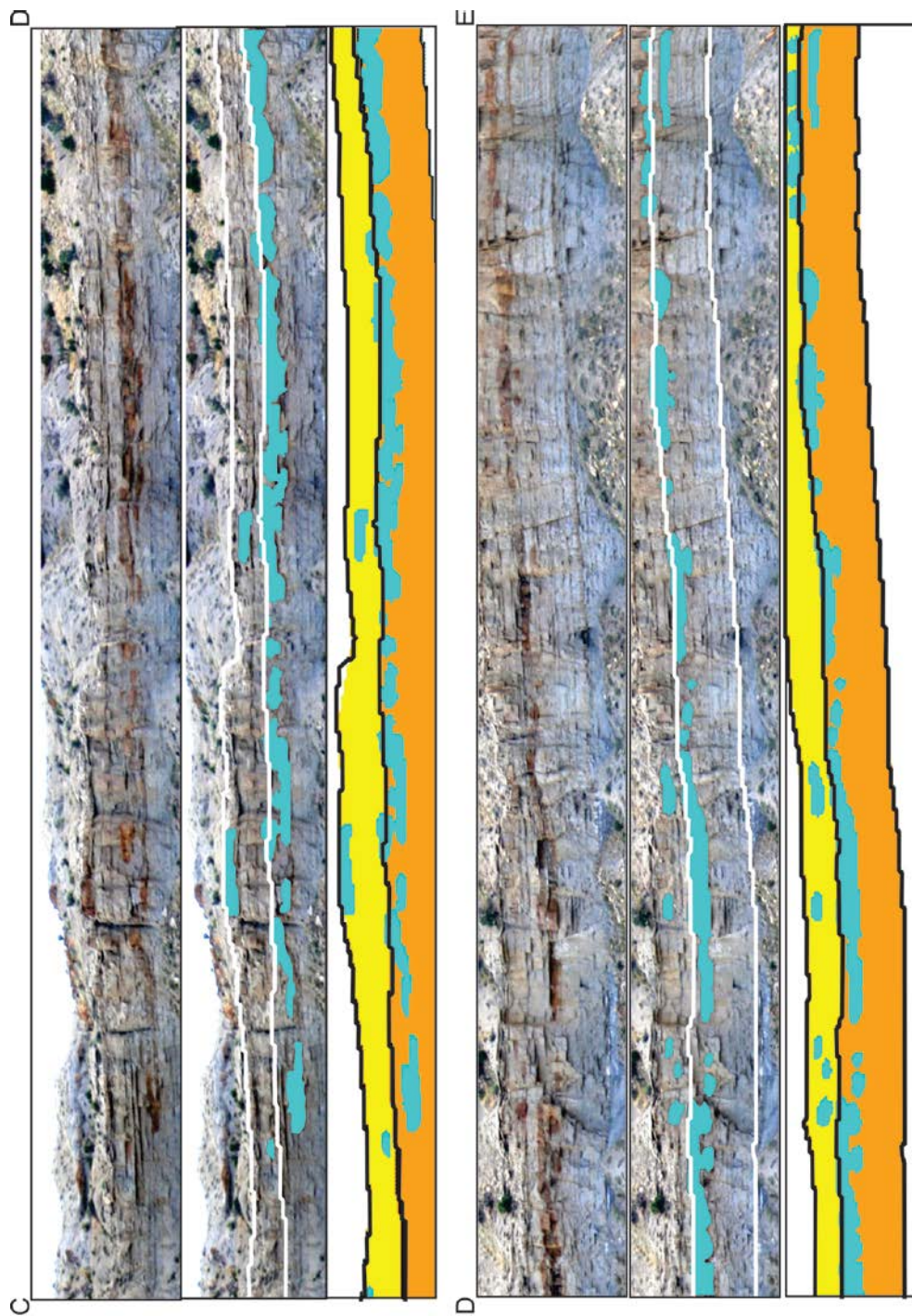




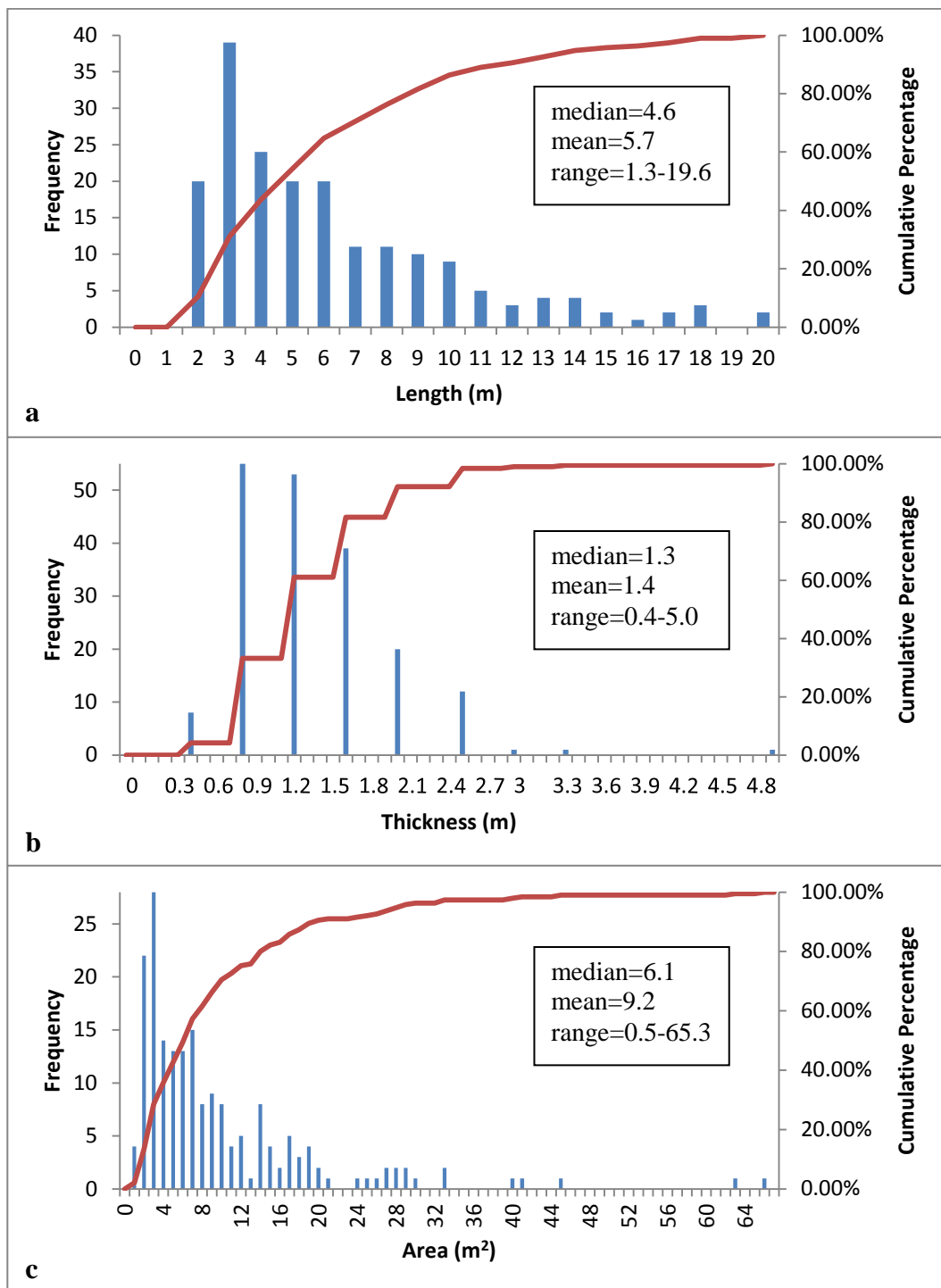
**Figure 3-14.** Histograms and plots of concrete (a) length, (b) thickness and (c) area versus cumulative percent at Garley Canyon.





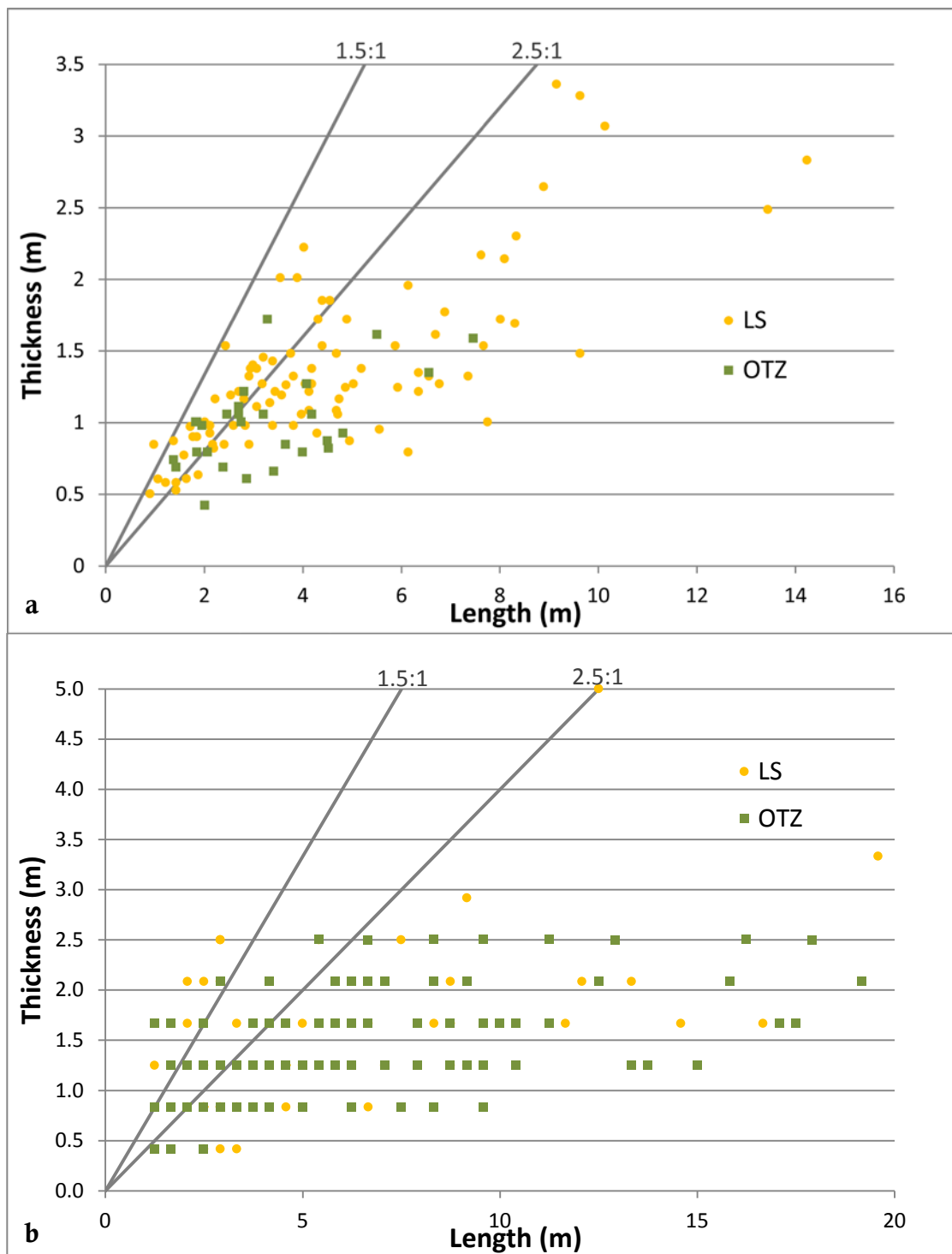


**Figure 3-15.** Facies and concretion distribution in a shoreface parasequence along the 700 m exposed outcrop face at Carbonville. (a) Photomosaic of the outcrop section that was used to measure the dimensions and distribution of concretions. (b) The concretions were outlined and the top and base of the studied parasequence and boundary between the lower shoreface and offshore transition zone were traced along the section as input for the (c) modelled reservoir grid of the outcrop.

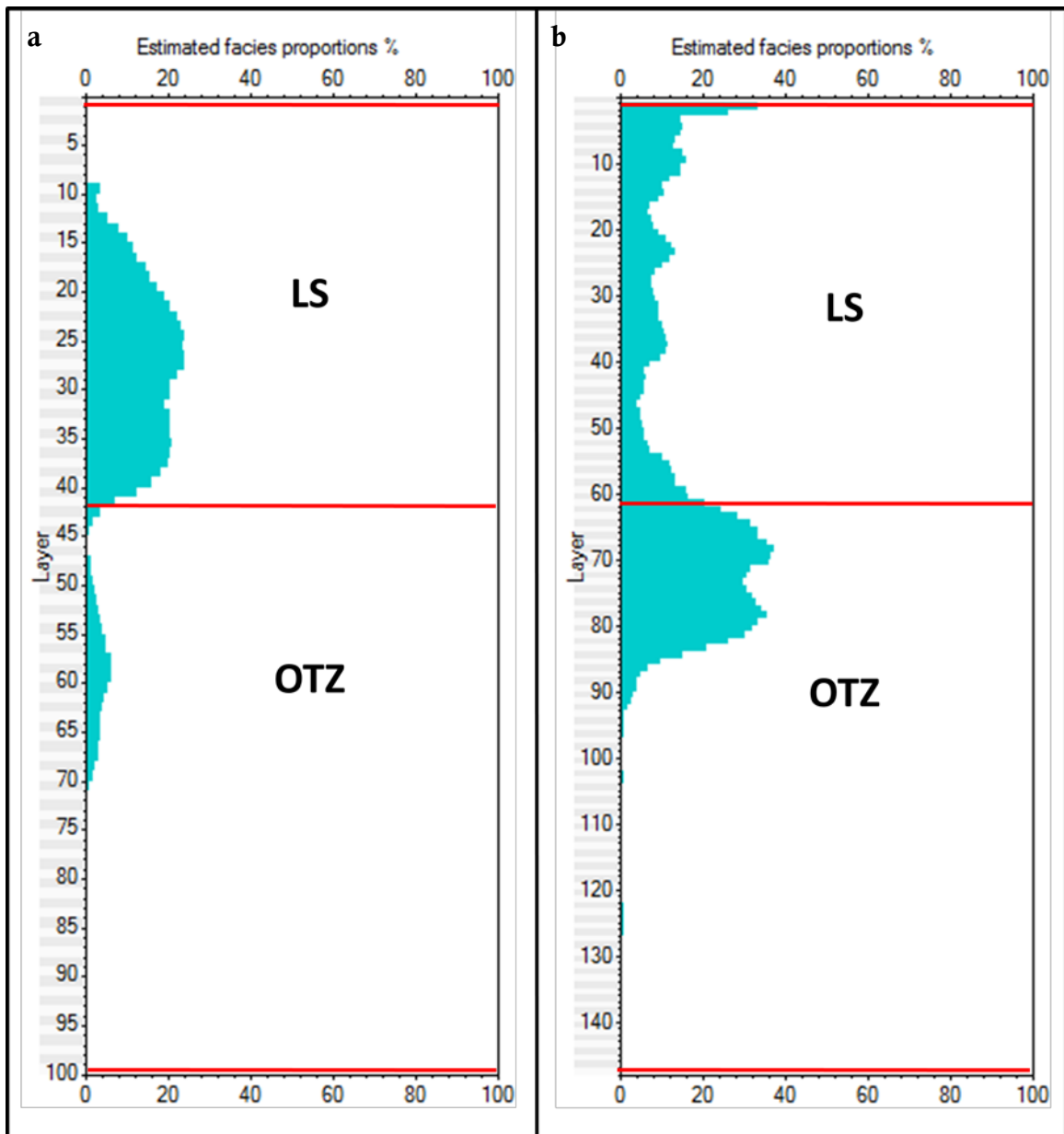


**Figure 3-16.** Histograms and plots of concrete (a) length, (b) thickness and (c) area versus cumulative percent at Carbonville.

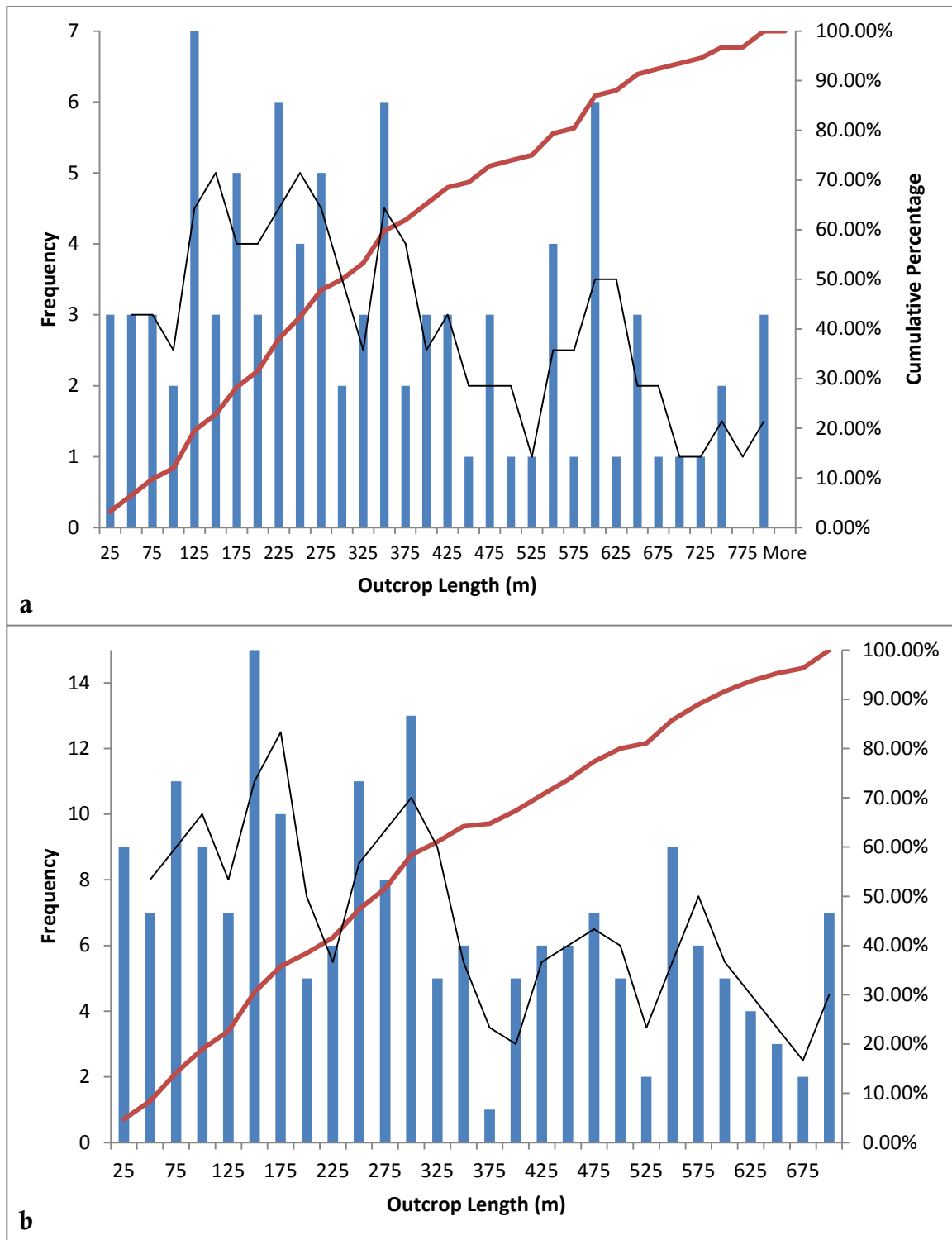




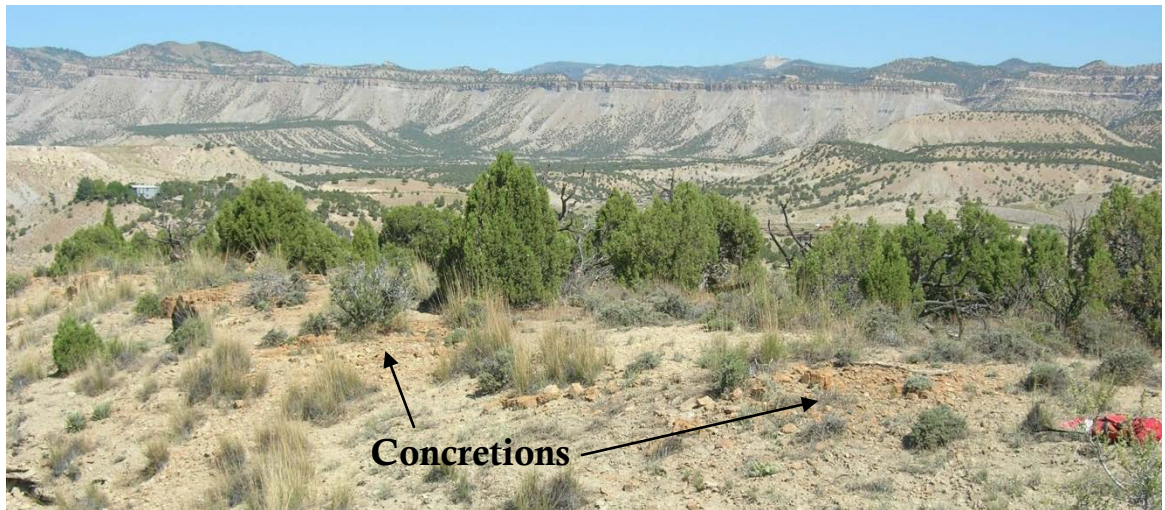
**Figure 3-17.** Crossplot of concretion length and thickness for (a) Garley Canyon and (b) Carbonville, showing that concretions with aspect ratios greater than 2.5:1 are classified as elongate, those less than 1.5:1 as equant and those of intermediate dimensions as subequant.



**Figure 3-18.** Vertical proportion curves of calcite from the measured outcrop sections at (a) Garley Canyon and (b) Carbonville. Both show a bimodal distribution of the vertical proportion of cement with the highest abundance occurring along the boundary between the lower shoreface (LS) and offshore-transition zone (OTZ) depositional environments. Cement abundance is highest in the LS at Garley Canyon, while it is highest in the OTZ at Carbonville.



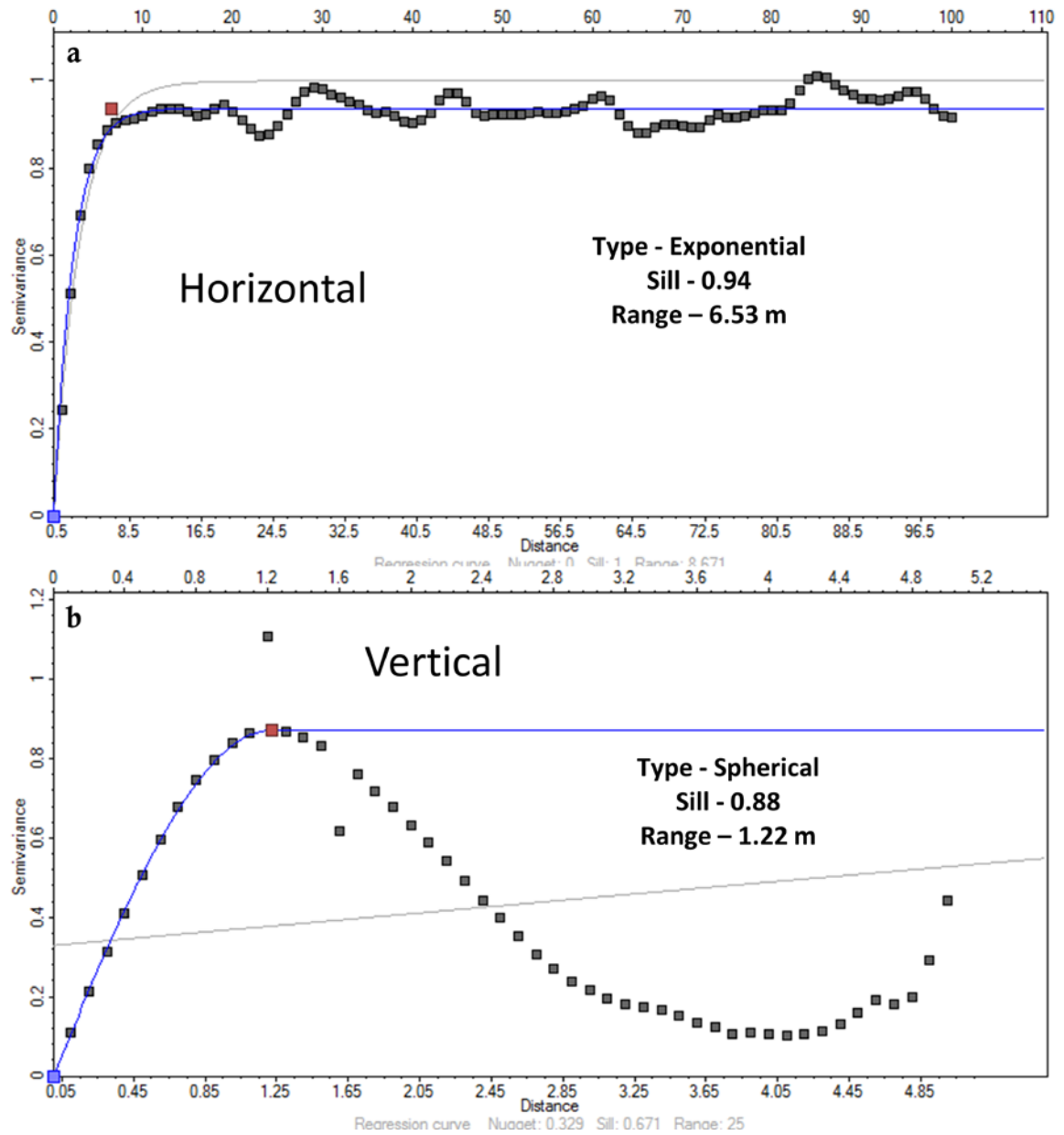
**Figure 3-19.** Horizontal frequency distribution of concretion centers along the (a) Garley Canyon and (b) Carbonville outcrop sections.



**Figure 3-20.** Plan view exposure of calcite concretions along the top of the Carbonville outcrop. The concretions are localized to the hummocks and appear to be randomly distributed.

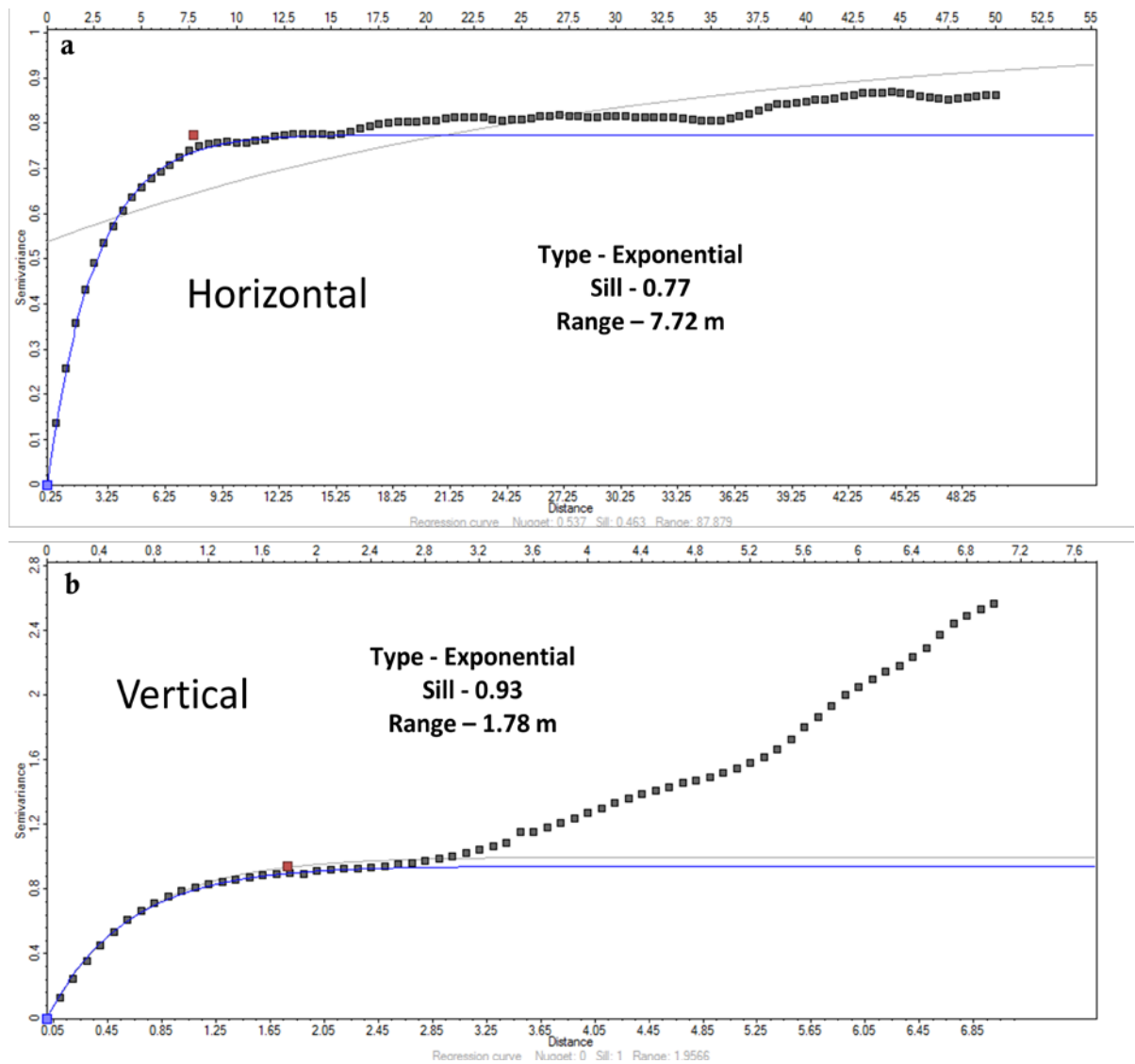


**Figure 3-21.** The Carbonville outcrop provides excellent three-dimensional exposures of calcite concretions.

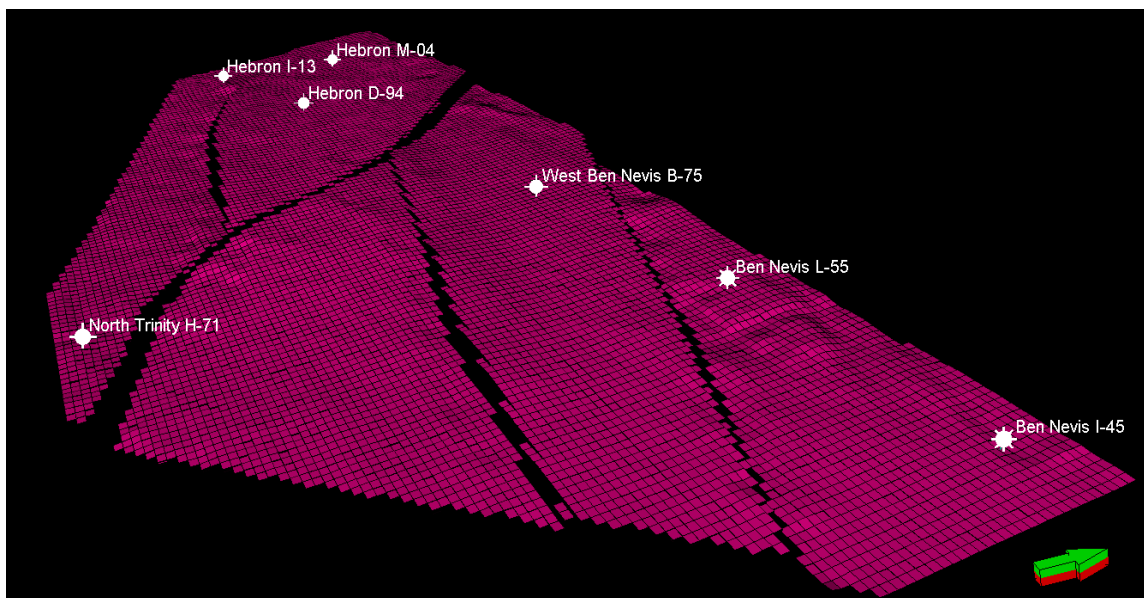


**Figure 3-22.** Modelled (a) horizontal and (b) vertical indicator variograms to describe the spatial distribution of cement in the Garley Canyon outcrop section.

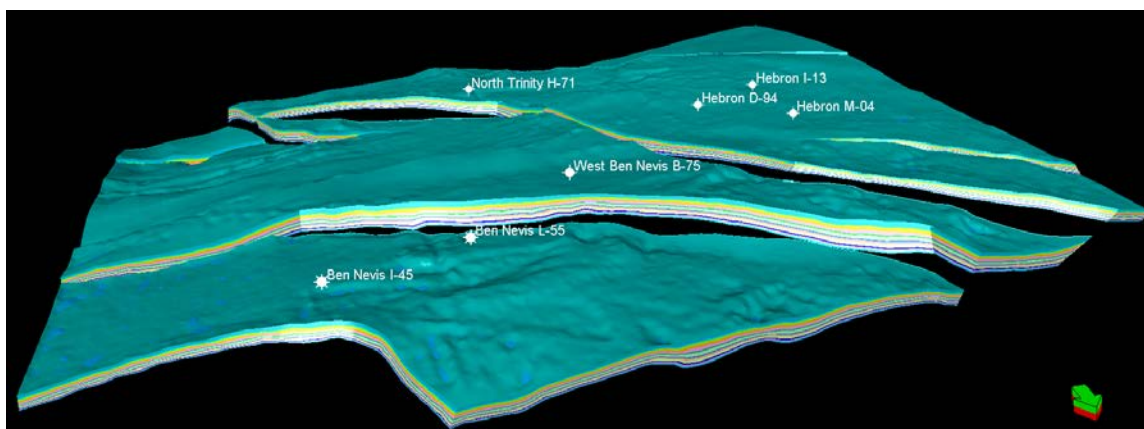




**Figure 3-23.** Modelled (a) horizontal and (b) vertical indicator variograms to describe the spatial distribution of cement in the Carbonville outcrop section.



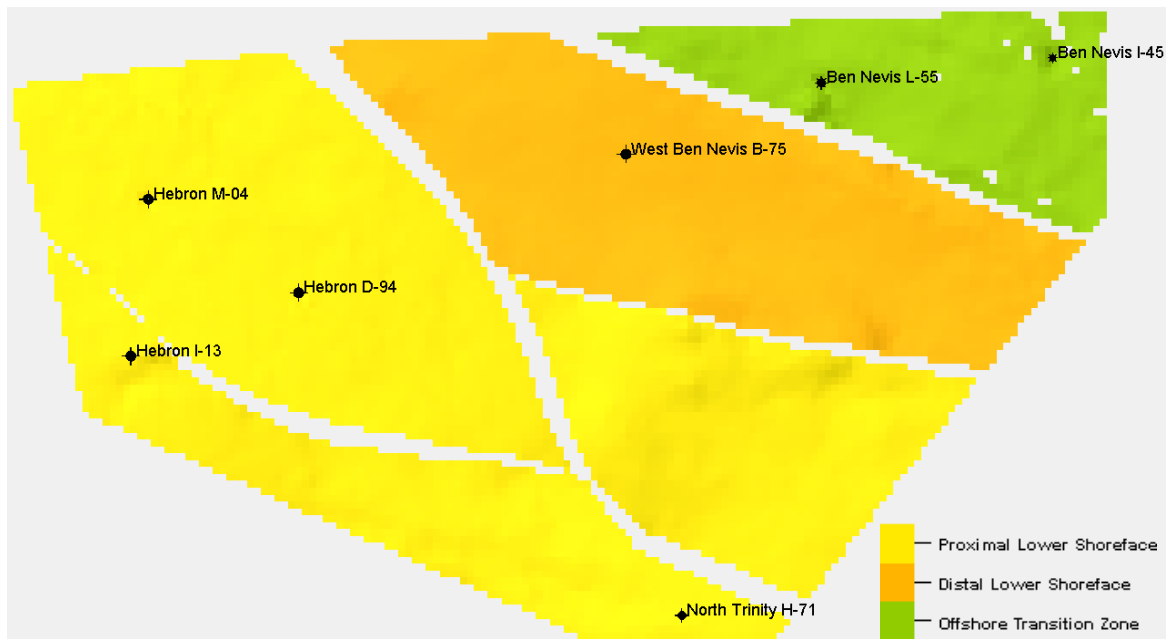
**Figure 3-24.** 3D reservoir model of the Hebron Asset constructed in the Petrel E&P Software Platform. Grid cell dimensions in the x and y directions are 100 m x 100 m. Arrow points towards north.



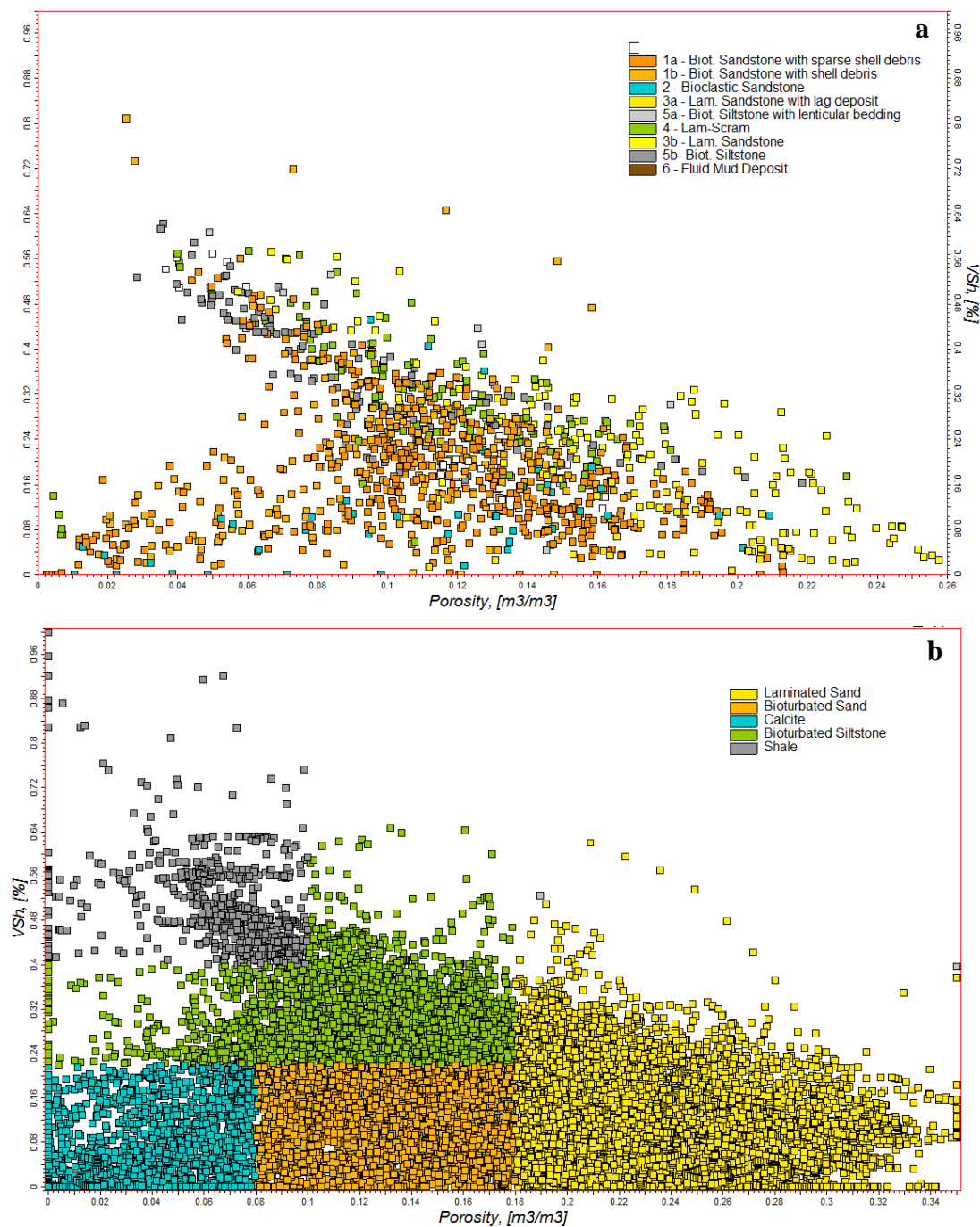
**Figure 3-25.** Structural model of the Hebron Asset created from seismically-interpreted faults and horizons. The top and base of the model is defined by the Ben Nevis and mid-Aptian Unconformity horizons and the reservoir is subdivided into 16 stratigraphic zones. Vertical exaggeration 2x. Arrow points towards north.







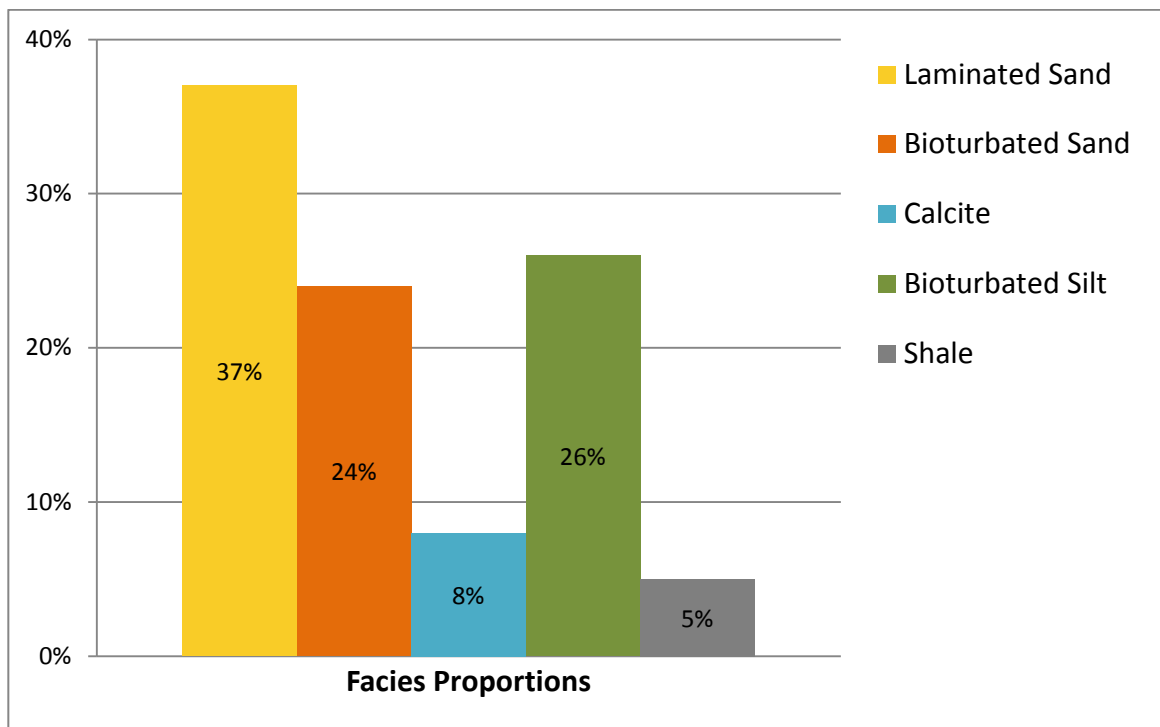
**Figure 3-27.** Environment of deposition map for the Ben Nevis Formation at the Hebron Asset, interpreted to be a wave-dominated shoreface setting. Map is approximately on the FSSB horizon.



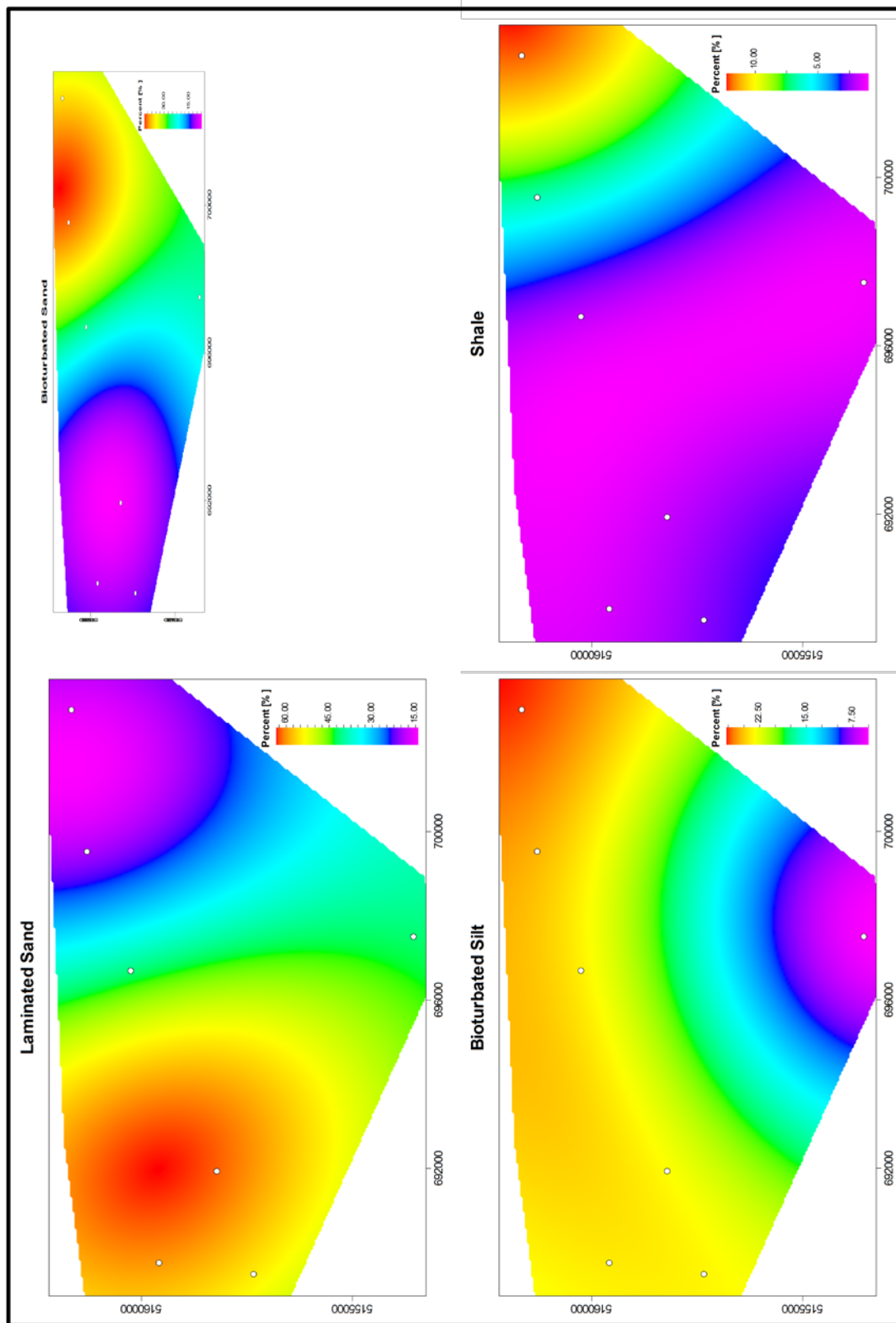
**Figure 3-28.** Cross-plot of porosity and  $V_{\text{shale}}$  for (a) Ben Nevis L-55 in relation to the sedimentary facies described in core and (b) wells in the Hebron Asset in relation to the facies classified for reservoir modelling.



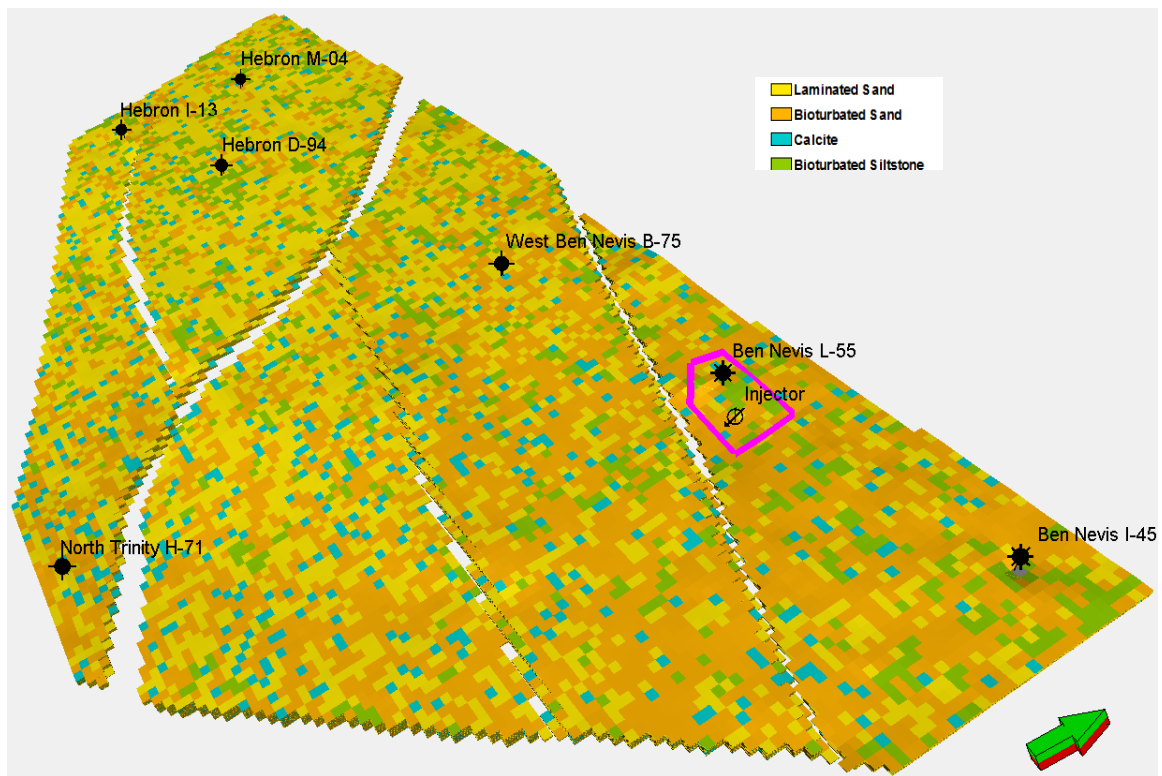
**Figure 3-29.** W-E cross-sectional view through the Hebron Asset of the stochastic population of facies conditioned to the well data.



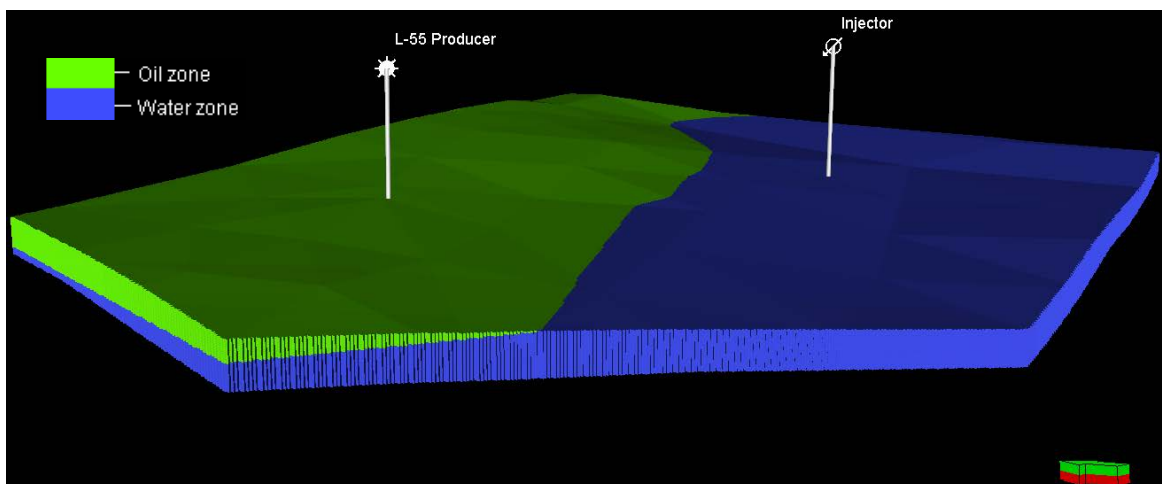
**Figure 3-30.** Histogram of global facies proportions encountered in the seven studied wells within the Hebron Asset.



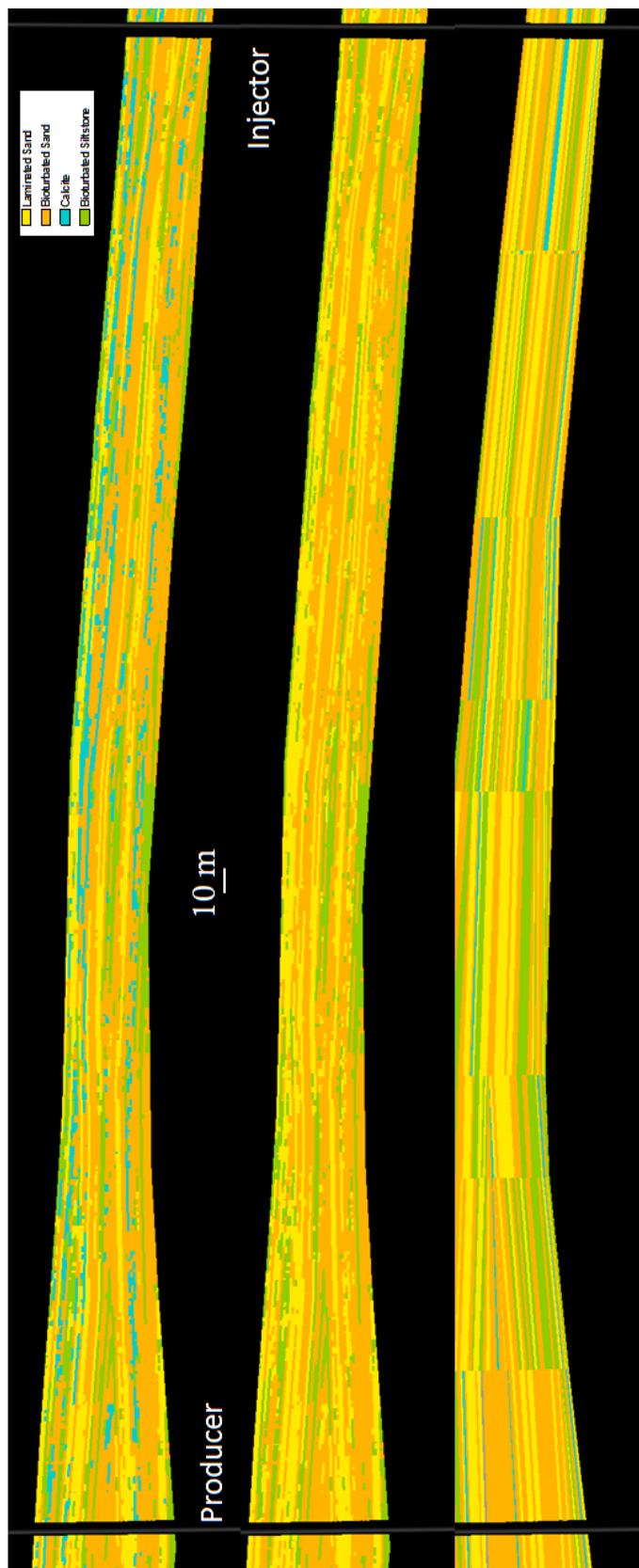
**Figure 3-31.** Facies proportion maps used to guide the stochastic population of facies in the Hebron Asset reservoir model.



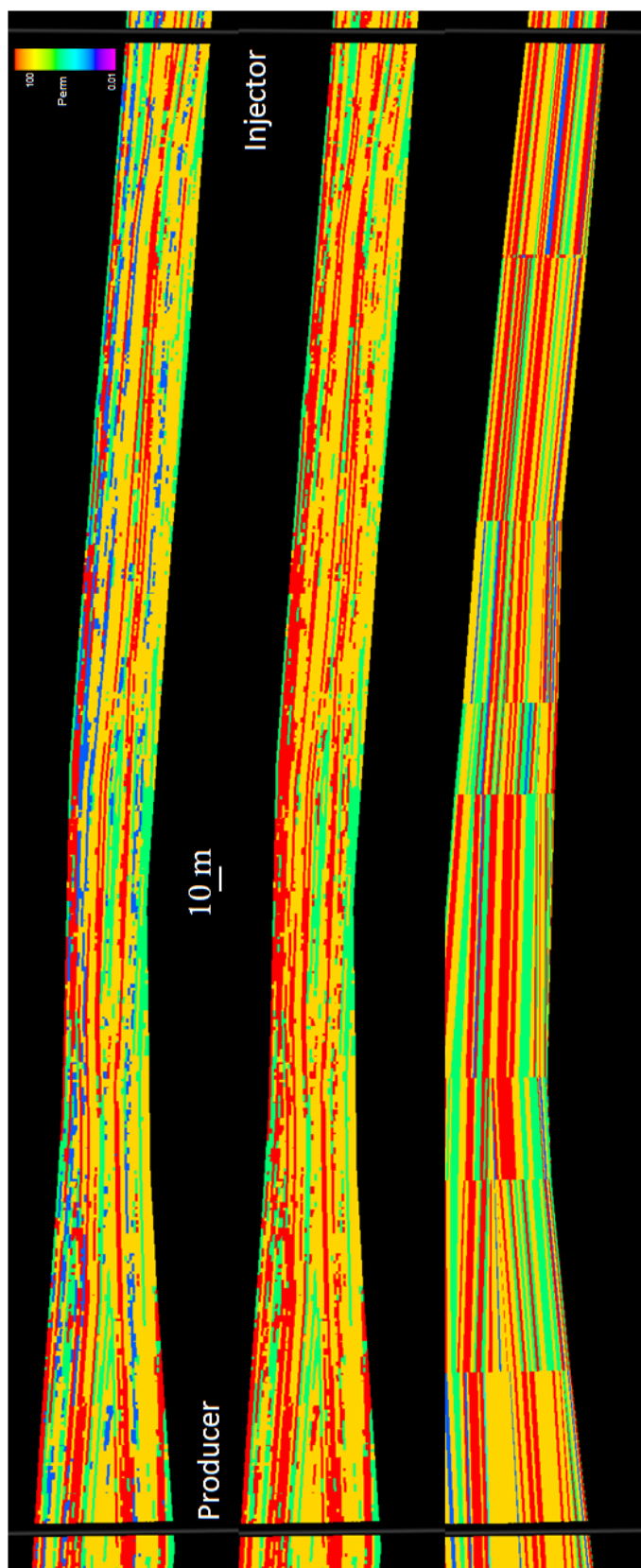
**Figure 3-32.** Populated facies shown on the FSSB horizon, which is the upper grid limit of the fine-scale L-55 sector model used for streamline simulation. The pink polygon outlines the sector grid boundary which includes a producer-injector pair used in the simulation.



**Figure 3-33.** 2m x 2 m sector model created around L-55 to model the measured outcrop dimensions of calcite concretions for use in the streamline simulation of a producer-injector pair.

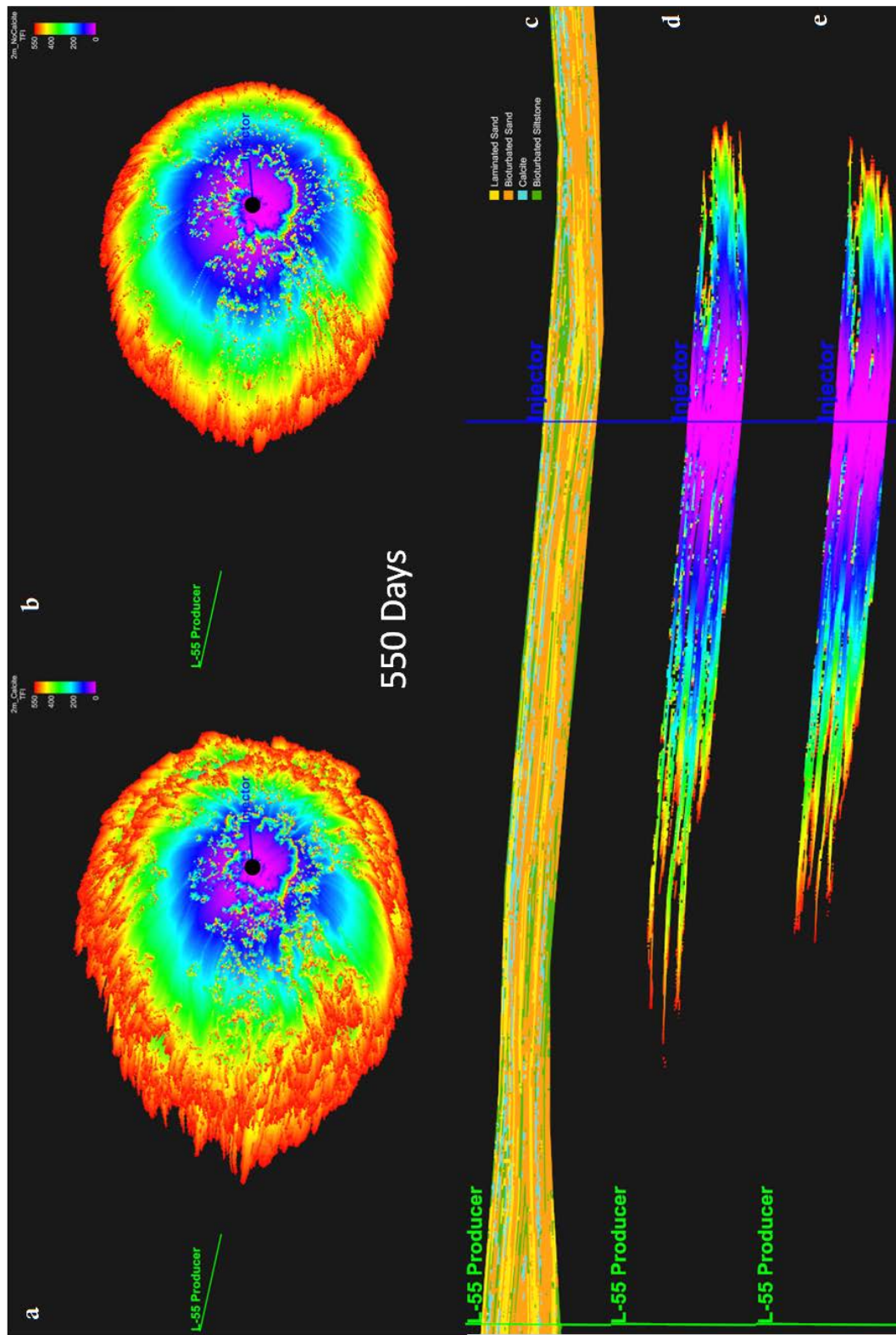


**Figure 3-34.** The modelled facies distribution between the producer-injector pair in (a) the fine-grid sector model. The population of calcite was conditioned to well and outcrop data. To compare the effects of (b) a model without calcite, laminated sand replaced the calcite in the populated facies model. (c) The coarser 100x100 m grid which is typically used in simulation was also simulated to demonstrate the effects of overestimating the size of concretions.

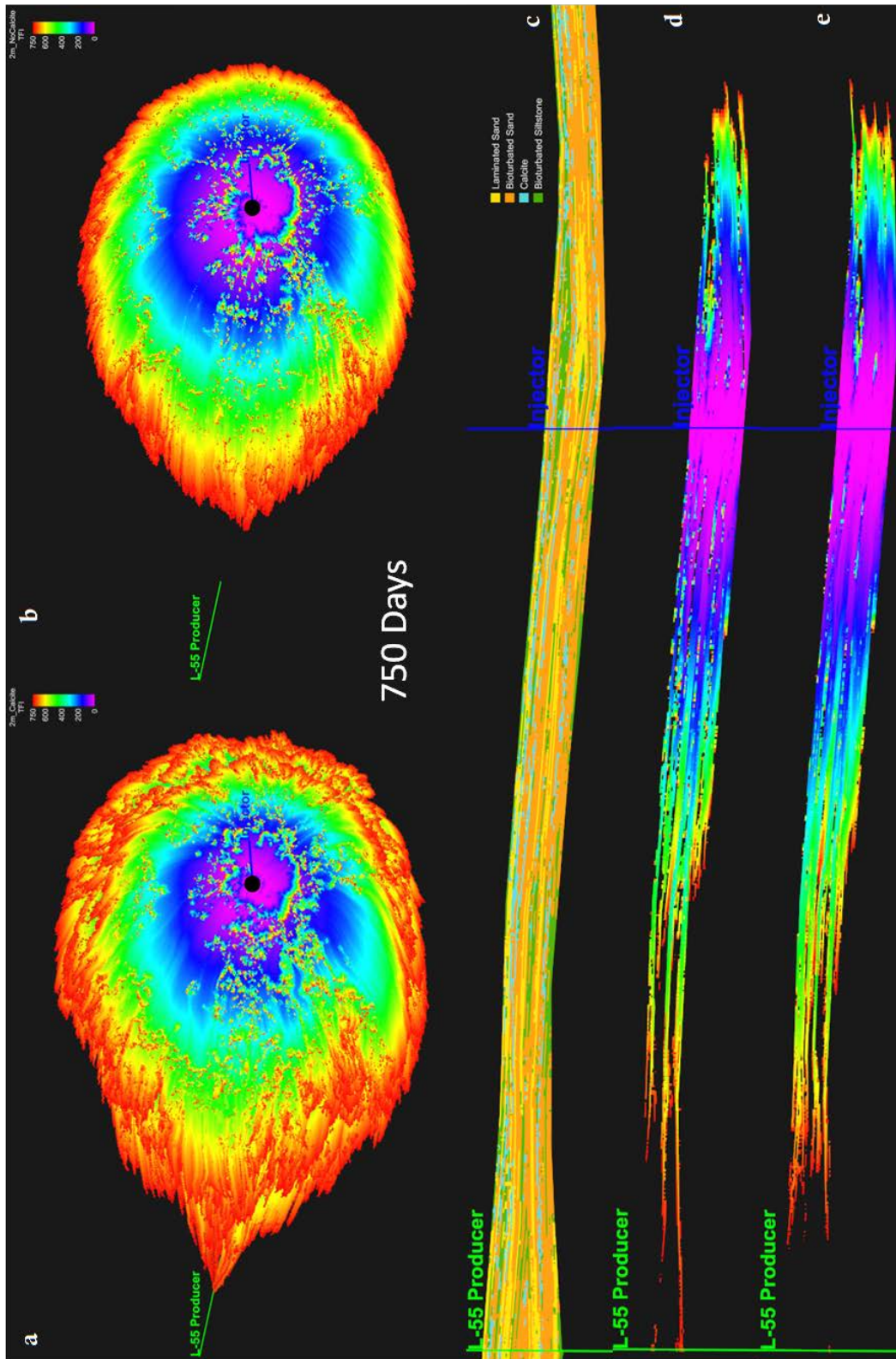


**Figure 3-35.** The modelled permeability distribution assigned by facies between the producer-injector pair in (a) the fine-grid sector model containing calcite; (b) the sector model without calcite; and (c) the coarser 100x100 m grid which is typically used in simulation.



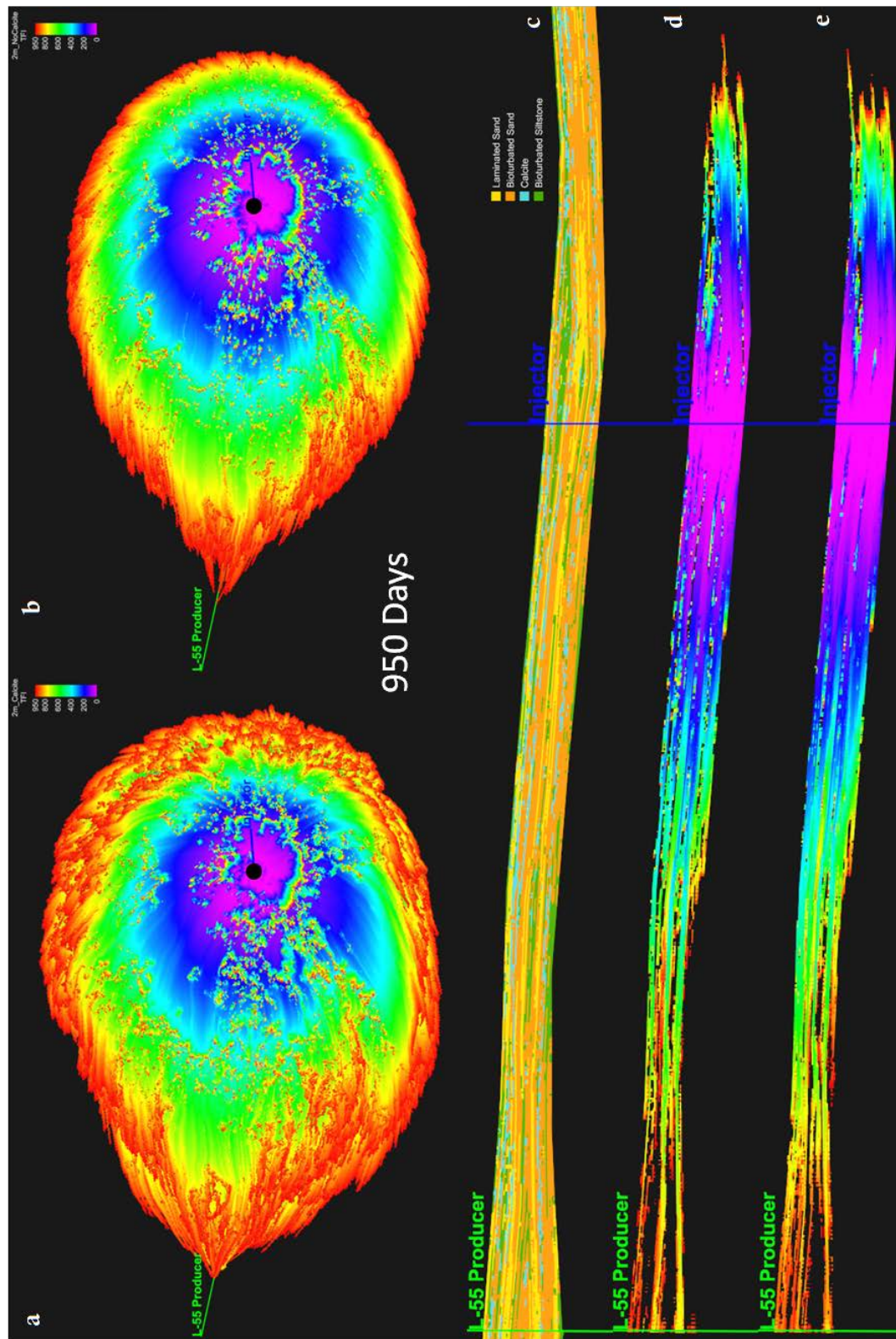


**Figure 3-36.** The location of the injection fluid front after 550 days of injection into the 2 m x 2 m Hebron sector model. The position of the fluid front is farther in the model (a) containing calcite than in that (b) not containing calcite. (c) The distribution of calcite between the producer and injector. The fluid front advances farther and is fingered, leaving more unswept regions in the model (d) containing calcite than in that (e) not containing calcite.

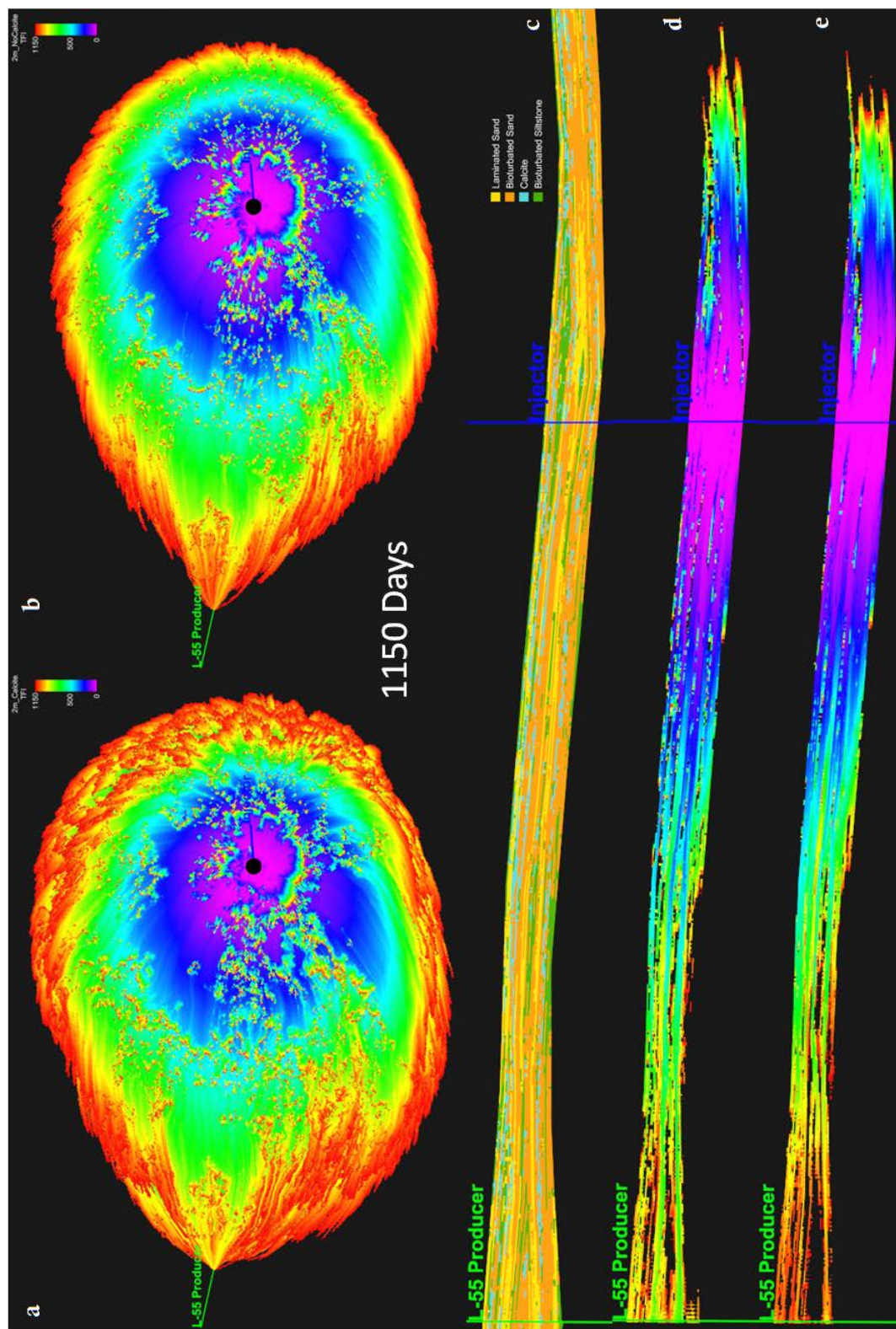


**Figure 3-37.** The location of the injection fluid front after 750 days of injection into the 2 m x 2 m Hebron sector model. The position of the fluid front is farther in the model (a) containing calcite than in that (b) not containing calcite. (c) The distribution of calcite between the producer and injector. The fluid front advances farther and is fingered, leaving more unswept regions in the model (d) containing calcite than in that (e) not containing calcite.



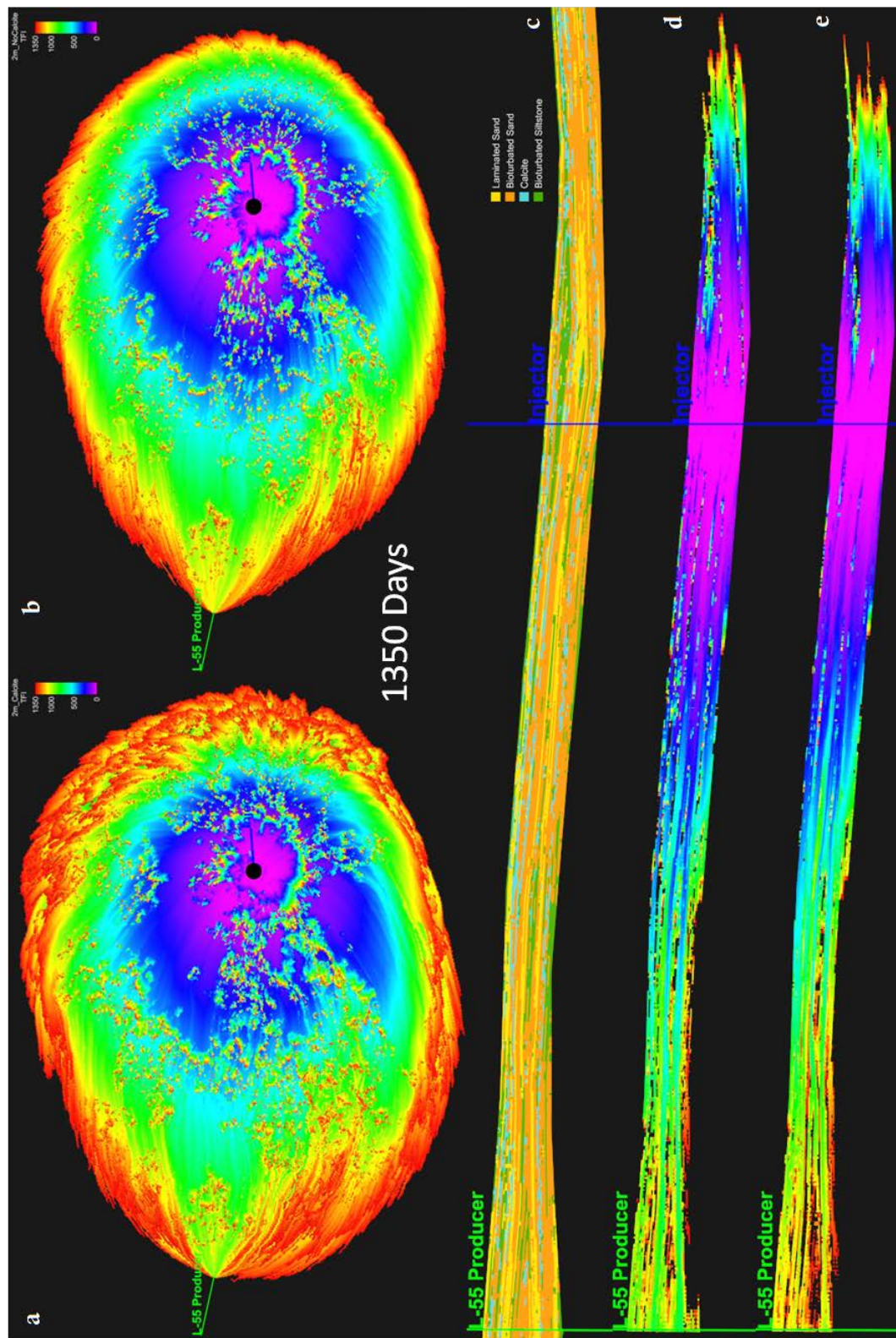


**Figure 3-38.** The location of the injection fluid front after 950 days of injection into the 2 m x 2 m Hebron sector model. The position of the fluid front is farther in the model (a) containing calcite than in that (b) not containing calcite. (c) The distribution of calcite between the producer and injector. The fluid front advances farther and is fingered, leaving more unswept regions in the model (d) containing calcite than in that (e) not containing calcite.

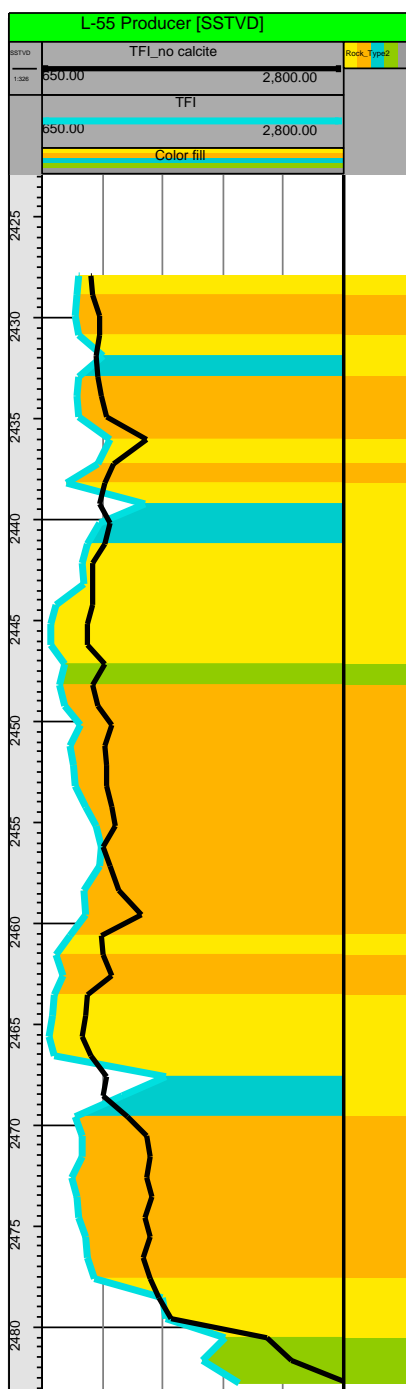


**Figure 3-39.** The location of the injection fluid front after 1150 days of injection into the 2 m x 2 m Hebron sector model. The position of the fluid front is farther in the model (a) containing calcite than in that (b) not containing calcite. (c) The distribution of calcite between the producer and injector. The fluid front advances farther and is fingered, leaving more unswept regions in the model (d) containing calcite than in that (e) not containing calcite.





**Figure 3-40.** The location of the injection fluid front after 1350 days of injection into the 2 m x 2 m Hebron sector model. The position of the fluid front is farther in the model (a) containing calcite than in that (b) not containing calcite. (c) The distribution of calcite between the producer and injector. The fluid front advances farther and is fingered, leaving more unswept regions in the model (d) containing calcite than in that (e) not containing calcite.



**Figure 3-41.** Breakthrough time logs for the L-55 producer in the model with calcite (blue line) and the model without calcite (black line). Breakthrough occurs earlier in the model with calcite. The distribution of facies in both models is shown.

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## **4 Conclusions**

Reservoir heterogeneity in shoreface deposits has significant effects on flow behaviour and an understanding of the distribution of reservoir properties is critical for subsurface reservoir development. The spatial distribution of porosity and permeability in reservoirs is controlled by depositional and diagenetic processes that create heterogeneities in sedimentary rocks. These heterogeneities create baffles or barriers to flow and have significant implications for fluid flow and hydrocarbon recovery. The ability to quantify geologic variability and predict reservoir continuity is critical to the accurate simulation of reservoir performance and hydrocarbon recovery.

Reservoir modelling of the Ben Nevis Formation at the Hebron Asset in this study integrated interpretations and information from sedimentological studies, facies models, sequence stratigraphic concepts, and analogue studies to create a geologically-realistic representation of the reservoir architecture and variability. Outcrop analogue data was used to supplement subsurface well data in this study to quantify the distribution, size and morphology of heterolithic and calcite-cemented facies within shoreface successions and provide a rational basis for incorporating calcite concretions into reservoir models that can accurately predict fluid behaviour.

1. A detailed sedimentological study of the Ben Nevis Formation at the Hebron Asset indicates that it is a shoreface deposit that is interbedded with fairweather facies and storm bed deposits. The heterolithic nature

reflects variable hydrodynamic energy conditions where large amounts of sediment were periodically supplied by storm activity or pulses of shoreface progradation into an otherwise quiescent depositional setting.

2. Log and core data indicate that the Ben Nevis Formation is a transgressive sequence of shoreface parasequences that displays an overall deepening trend and a landward shift in the deposition of more distal facies of lower reservoir quality. Facies that are representative of lower shoreface and offshore-transition zone depositional environments were identified in the well data and stochastically populated within the reservoir model. Proportion histograms, vertical proportion curves, variogram models and facies proportion maps, guided by the conceptual depositional model generated as part of this study, describe the spatial distribution of facies.
3. The Ben Nevis Formation contains abundant calcite cement that occurs in otherwise high reservoir quality sandstones. Well log and core data provide information about their stratigraphic occurrence within the formation and outcrop analogue data provides information about their morphology and spatial distribution. Detailed mapping of calcite concretions in outcrops of shoreface parasequences in the Book Cliffs, Utah provide data with respect to the size and occurrence of concretions and was used to generate geostatistical descriptions of their spatial distribution. Variogram calculations reveal a horizontal:vertical anisotropy ratio of 5:1 that was applied to the well-defined vertical variograms in the Hebron reservoir model to stochastically populate

low permeability calcite cements in the shoreface reservoir. This is the first time that this has been possible to do in a logical and considered manner, and will likely be widely used in modelling similar reservoirs, at least semi-regionally.

4. Streamline simulation demonstrates the impact that diagenetic alteration of a hydrocarbon reservoir by calcite cement has on fluid flow behaviour. The precipitation of calcite cement in otherwise high reservoir quality host rock, results in a variability in permeability distribution within the reservoir. Streamline simulation links the dynamic reservoir characteristics with the static reservoir characteristics and shows how fluid flow is controlled by geologic heterogeneity. Concretions were modelled in a fine-resolution sector model (2 m x 2 m x 1 m) of the Ben Nevis Formation at the Hebron Asset to represent a realistic distribution of calcite cement. Single-phase simulation demonstrates that concretions affect flow paths by making them more tortuous, leaving unswept regions behind concretions, and resulting in earlier breakthrough.

This study used core, well log, and outcrop analogue data to create an integrated approach for the reservoir characterization of the Ben Nevis Formation. This approach improves the understanding on the controls on reservoir quality and the distribution and impacts of low-permeability heterogeneities and creates a reservoir model that better predicts the occurrence of heterolithic and calcite-cemented facies









within shoreface reservoirs. The improved model aids in the prediction of flow response and is fundamental for optimal reservoir development.

## **Appendix A**















### **Sedimentological Core Descriptions**




# SYMBOLS FOR CLASTIC CORE LOGGING

## CONTACTS









-  = EROSIONAL, sharp
-  = CONFORMABLE, sharp
-  = GRADATIONAL > 1 cm
-  = GRADATIONAL < 1 cm
-  = WAVY
-  = STEEP, overhanging
-  = CONVEX or CONCAVE
-  = INCLINED

## STRUCTURES - PHYSICAL













-  = PLANAR-PARALLEL laminae
-  = LAMINAE or BED THICKNESS (1-10)
-  = CROSS-BEDDING (general, w/ dip angle)
-  = PLANAR (2D)
-  = TROUGH (3D)
-  = LOW-ANGLE INCLINED CROSS-STRATA
-  = SYMMETRIC RIPPLES
-  = ASYMMETRIC RIPPLES
-  = IRREGULAR BEDDING
-  = GRADED BEDDING
-  = NO APPARENT BEDDING
-  = FLASER BEDDING (F-F-F)
-  = WAVY BEDDING (W-W-W)
-  = LENTICULAR BEDDING (L-L-L)

-  = MUD CRACKS
-  = SLUMP, contorted bedding
-  = LOAD CAST

## STRUCTURES - BIOGENIC

-  = ROOTS
  -  = slight  $\leq 30\%$
  -  = moderate 30-60%
  -  = strong 60-90%
  -  = CHURNED (inferred = )
  -  = BORING, BORED SURFACE
  -  = SKOLITHOS *Isp*, OPHIOMORPHA *Isp*, PLANOLITES *Isp*, etc.
- degree of  
BIOTURBATION  
(% surface area)

## CONSTITUENTS

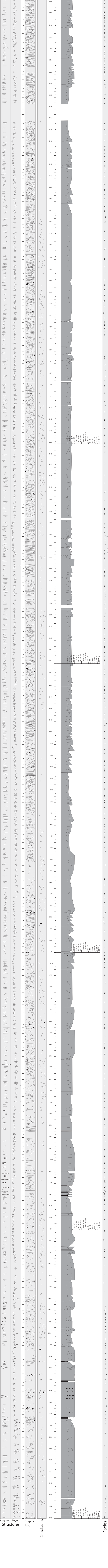
-  = LITHOCLASTS
  -  = CHERT
  -  = SHALE
  -  = CARBONATES
-  = BIOCLASTS
-  = CALCITE; calcareous
-  = DOLOMITE; dolomitic
-  = QUARTZ; quartzose
-  = CHERT; cherty
-  = GLAUCONITE; glauconitic
-  = FELDSPAR; feldspathic
-  = PYRITE; pyritic

⑤ Siderite  
clast

S = SIDERITE;

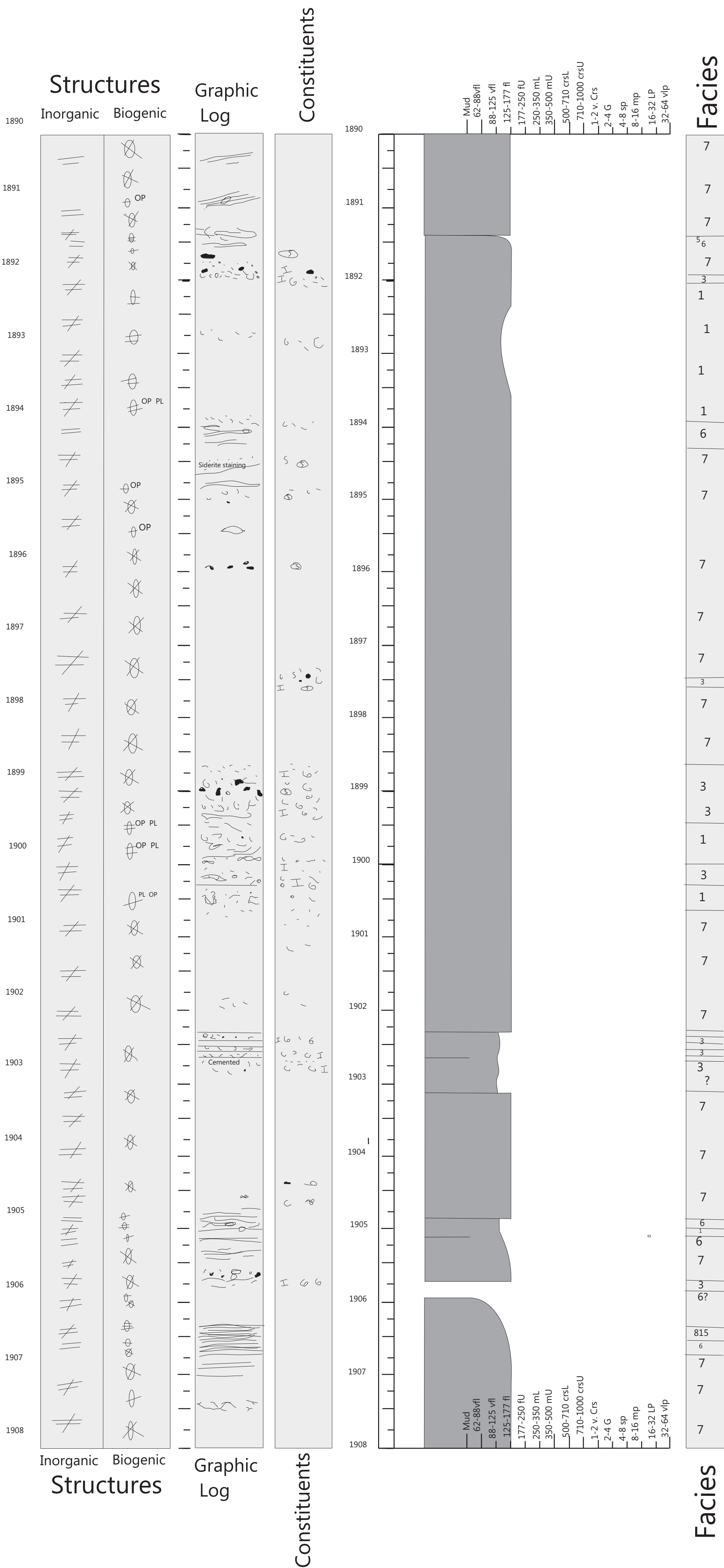


# Bell NEVIS L-33

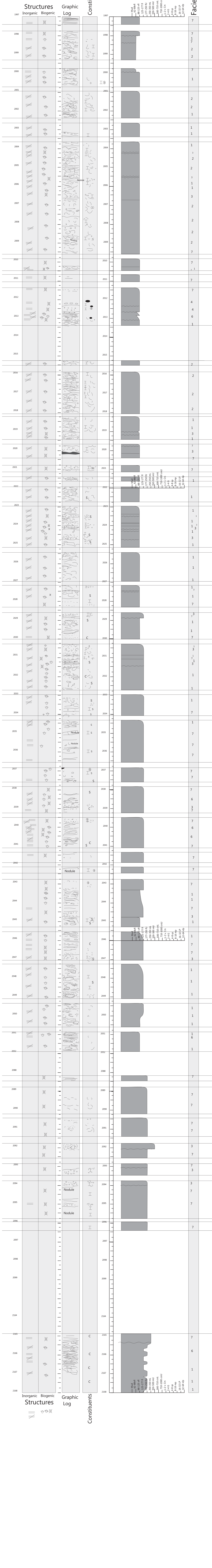




# Hebron I-13



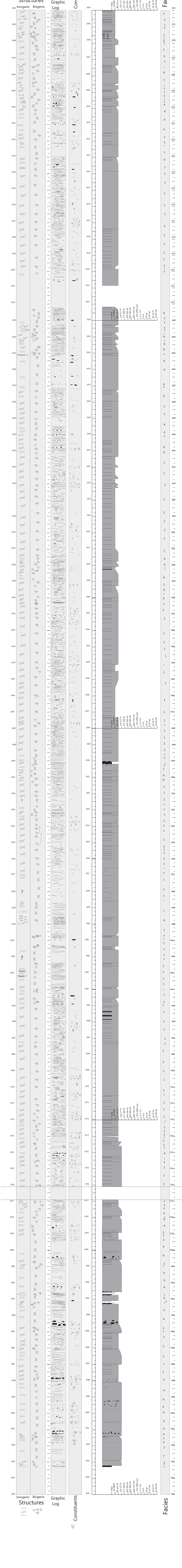
# North Trinity H-71





# West Ben Nevis

## B-75



## **Appendix B**

### **Bioturbation influence on reservoir quality: A case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada**



# *Bioturbation influence on reservoir quality: A case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada*

**Nicola S. Tonkin, Duncan McIlroy, Rudi Meyer, and Allison Moore-Turpin**

## **ABSTRACT**

The delineation Ben Nevis L-55 well, located in the Hebron-Ben Nevis field, offshore Newfoundland, targeted the Cretaceous Ben Nevis Formation in the petroleum-rich Jeanne d'Arc Basin. This case study focuses on the bioturbated net-pay horizons and assesses the importance of animal-sediment interactions in controlling the porosity and permeability of sandstone reservoir intervals. Our data reveal that bioturbation can either reduce permeability and porosity by as much as approximately 33% or enhance it by up to 600%, dependent on burrow type and behavior of the trace-making organism.

The net-pay interval in the cored interval of Ben Nevis L-55 is characterized by *Ophiomorpha*-dominated ichnofabrics. The action of bioturbators can be classified in terms of sediment mixing, sediment cleaning, sediment packing, and pipe-work-building strategies. Bioturbation has the potential to (1) increase isotropy or uniformity of grain size by destroying sedimentary laminae through burrow homogenization, or (2) decrease isotropy by selectively sorting grains into burrow lining and fill by grain size, and through creation of open-burrow systems filled with later sediments of differing character to the host sediment. The petrophysical characteristics of the reservoir facies are highly dependent on trace fossil morphology, presence or absence of burrow linings, nature of burrow fills, burrow size,

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Nicola Tonkin received her M.Sc. degree in geology from the University of Auckland, New Zealand. She is currently a Ph.D. candidate at Memorial University. Her dissertation focuses on the importance of animal-sediment interactions in controlling porosity and permeability. Her main research interests are the integration of sedimentology and ichnology and their application to paleoenvironmental reconstruction, sequence stratigraphy, and reservoir characterization.

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Duncan McIlroy is a Canada Research Chair in petroleum geology at Memorial University in Newfoundland. His current research interests are broadly focused on using integrated sedimentology and ichnology to refine paleoenvironmental analysis and reservoir characterization. His work is of significance in the study of conventional sandstone and shale gas reservoirs and provides research opportunities for several graduate students.

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Rudi Meyer earned his Ph.D. in clastic reservoir sedimentology from the University of Calgary in 1998. Prior to his Ph.D., he worked at Petroleos de Venezuela S.A., focusing on development geology in the Maracaibo Basin. His current research interests are integrated reservoir characterization, progressive development of multidirectional pore geometries and permeability during diagenesis, and teaching and learning methods in geoscience.

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on 3-D reservoir modeling. She holds a B.Sc. (honors) degree in Earth sciences from Memorial University, where she is currently a graduate student. Her research interests are in sedimentary geology, reservoir characterization, and modeling.

## ACKNOWLEDGEMENTS

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and bioturbation intensity. Mudstone-rich facies and ichnofabrics containing mudstone-filled and/or lined burrows (e.g., *Ophiomorpha* and clusters of *Chondrites*) have the net effect of permeability reduction. In contrast, permeability enhancement is documented from muddy sandstone facies with clean sand-filled burrows (e.g., *Thalassinoides*) and clean sandstones with burrow-mottled or diffuse to massive textures.

## INTRODUCTION

Many of the world's most productive siliciclastic petroleum reservoirs are strongly bioturbated, including the Lower Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada; Upper Jurassic Fulmar Formation and Middle Jurassic Brent Group, North Sea, United Kingdom; Middle Jurassic Ile Formation, Halten Terrace, offshore mid-Norway; and Lower Cretaceous McMurray Formation, Alberta, Canada (McAlpine, 1990; Richards, 1992; Cannon and Gowland, 1996; McIlroy, 2004; Crerar and Arnott, 2007). Effective production of hydrocarbon reservoirs requires reliable prediction of facies-related reservoir properties and correlation at the interwell scale. Hence, specifically in bioturbated settings, facies analysis and reservoir characterization are reliant upon description and interpretation of bioturbation and ichnofabrics from conventional core (Martin and Pollard, 1996).

Ichnofabric analysis is an approach used to describe the sedimentology and ichnology of a horizon in terms of diversity, bioturbation intensity, and colonization history (Bromley and Ekdale, 1986; Taylor and Goldring, 1993; Taylor et al., 2003). An integrated approach to the prediction of reservoir quality in bioturbated reservoir intervals involves the study of ichnofabric in core and further laboratory-based analysis. The same principles have also been used to improve the productivity of aquifers (Cunningham et al., 2009).

This research is aimed at generating a more complete understanding of the function that organisms have in controlling the porosity and permeability of sandstone reservoirs at the reservoir scale. The studied core (BN L-55) was taken from Ben Nevis field, in which the primary reservoir target is the Ben Nevis Formation. This sandstone-dominated reservoir is variably intensely bioturbated, with intensity of bioturbation being strongly facies controlled. *Ophiomorpha* burrows are the most conspicuous element of the ichnofauna throughout the well and are characteristic of several net-pay intervals. This study is focused on reservoir-quality changes directly associated with *Ophiomorpha* ichnofabrics.

To determine the influence that bioturbation has on petrophysical properties, 129 m (423 ft) of core was studied ichnologically and sedimentologically. Core descriptions are supplemented by ichnofabric analysis and detailed petrophysical analysis of net-pay horizons. Bioturbated reservoir zones from the Ben Nevis L-55 core were studied using the following techniques: (1) core logging from both a sedimentological and ichnological (ichnofabric assignment) perspective, including visual estimation of bioturbation intensity; (2) porosity estimated using dye-impregnated petrographic thin sections and digital imaging software; (3) creation of 88 large thin slices (*sensu* Garton and McIlroy, 2006); and (4) probe permeametry.

## REGIONAL SETTING

The Jeanne d'Arc Basin, offshore Newfoundland, contains several petroleum reservoirs in three fields producing at present (Hibernia, Terra Nova, and Whiterose), with the Hebron-Ben Nevis field slated to come on-stream next. The basin is located approximately 350 km (217 mi) southeast of St. John's, Newfoundland, on the northeast Grand Banks (Figure 1). The Jeanne d'Arc Basin developed in response to three rifting episodes that occurred during the Late Triassic to Early Cretaceous (Hubbard et al., 1985; Tankard and Welsink, 1987; Sinclair, 1988). The Ben Nevis Formation was deposited during the last documented episode of rifting (Sinclair, 1993). The base of the Ben Nevis Formation is marked by the middle Aptian unconformity, which has been related to uplift and erosion during continental breakup (Tankard and Welsink, 1987; Tankard et al., 1989).

The Ben Nevis field is part of the Hebron-Ben Nevis complex of fault blocks, offshore Newfoundland, Canada (see Figure 1). The field was discovered in July 1980 and has two wells drilled to date. The discovery well, Mobil et al. Ben Nevis I-45 (1980), drilled multiple targets from the Ben Nevis to the Hibernia Formation, whereas the delineation well, Chevron et al. Ben Nevis L-55 (1999), targeted the Ben Nevis Formation alone. Ben Nevis L-55 was drilled to a vertical subsea depth of

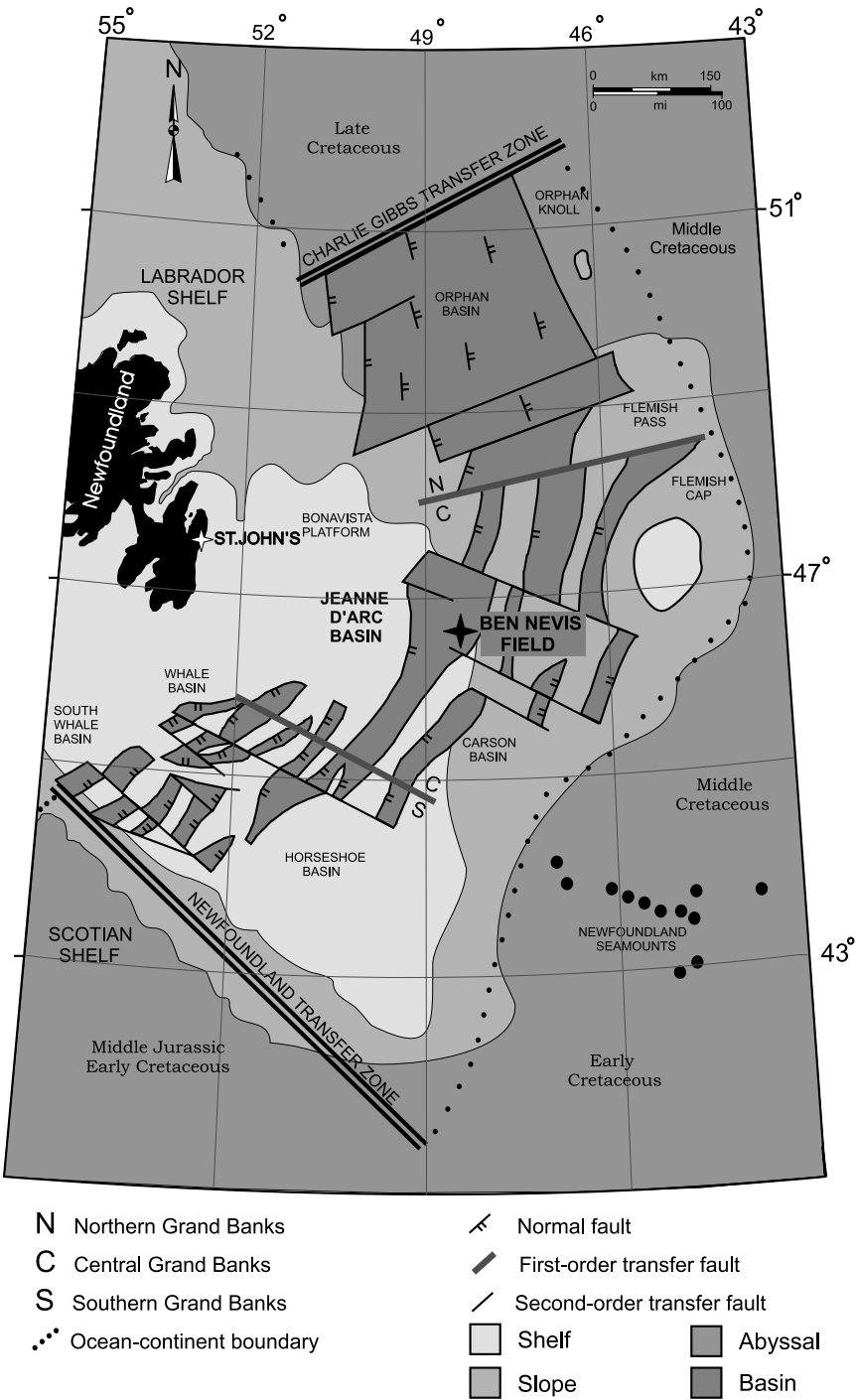
2650 m (8694 ft), from which 129 m (423 ft) of core was recovered from the upper Ben Nevis Formation between 2452 and 2320 m (8045 and 7611 ft) vertical subsea depth. The base of the Ben Nevis Formation was not drilled at the L-55 location. The cored interval includes 82 m (268 ft) of net porous sandstone with a net-to-gross ratio of 29% based on a petrophysical cutoff of 15%. Most of the net-porous sandstone occurs in bioturbated intervals and is concentrated in the lower half of the core (see Table 1). The Ben Nevis field is estimated to contain resources of 429 bcf (12.1 billion m<sup>3</sup>) of gas and 114 million bbl oil within three petroleum reservoirs: (1) the Ben Nevis Formation, (2) the Eastern Shoals Formation, and (3) the Hibernia Formation (C-NLOPB, 2008).

The Kimmeridgian Egret Member is recognized as the primary source rock in the Jeanne d'Arc Basin reservoirs, an organic-rich shale deposited in euxinic conditions (Von der Dick, 1989). The terrestrial organic-rich Gambo Member forms the base of the Ben Nevis Formation, and it is suggested that this is the source of carbonaceous debris within the upper part of the formation (Sinclair, 1993). The fining-upward shallow-marine succession is overlain by the transgressive marine Nautilus Shale (McAlpine, 1990), which acts as a reservoir seal. A back barrier and shoreface depositional setting for the Ben Nevis Formation was first proposed by Sinclair (1988, 1993).

Bioturbation is recognized in the Ben Nevis Formation (Tankard and Welsink, 1987; Sinclair, 1988, 1993; McAlpine, 1990; Driscoll et al., 1995; Pemberton et al., 2001; Spila et al., 2007) but has not previously been directly linked with improved reservoir quality. Highly bioturbated sandstones and siltstones of the Ben Nevis Formation of the Hibernia field have been interpreted as shoreface sandstones and tidal inlet channels in a barrier-island system (Tankard and Welsink, 1987; Sinclair 1993).

A detailed ichnological and sedimentological study of the Avalon and Ben Nevis formations, based on nine wells in the Jeanne d'Arc Basin, allowed recognition of several depositional settings, including fluviodeltaic, tidal flat, salt marsh, barrier island to lagoon, and shoreface to offshore environments

**Figure 1.** Sedimentary basins of the Grand Banks, offshore Newfoundland, Canada, including the Ben Nevis field within the petroleum-rich Jeanne d’Arc Basin. The rift basins are separated from the Scotian and Labrador shelves by the Newfoundland and Charlie Gibbs fracture zones, respectively (redrawn from Tankard and Welsink, 1987).



(Pemberton et al., 2001). Ichnofacies recognized from the shoreface and embayment settings in the upper Ben Nevis Formation fall within the *Skolithos* and *Cruziana* ichnofacies and include recognition of several *Glossifungites* surfaces (Pemberton et al., 2001). To date, no published sedimentological or ichnological study has been undertaken on the Ben Nevis L-55 core.

### METHODS

Three methods were used to describe the influence of bioturbation on porosity and permeability on five center-cut core-slab samples taken from the net-pay zone in the Ben Nevis L-55 core interval: conventional thin sections, large thin slicing and probe permeametry. Two slices of 3–5-mm



**Table 1.** Ben Nevis L55 Core Interval Summary of Lithofacies, Ichnofabric, Bioturbation Intensity, and an Idealized Graphic Log\*

Graphic Log	Lithofacies (LF)	Ichnofabrics	Bioturbation Intensity	Core-Plug Analysis		Core-Slab Samples	
				Porosity (%)	Permeability (md)	Porosity (%)	Permeability (md)
Fairweather deposition	Bioturbated sandy mudstone (LF5)	<i>Ophiomorpha</i> dominated, <i>Ophiomorpha-Phycosiphon</i> , <i>Ophiomorpha-Asterosoma</i> , and <i>Teichichnus-Phycosiphon</i> .	60 to >90%	15.7 (6) 10.5 to 20.3	15.8 (6) <0.1 to 63.4	Not sampled	Not sampled
	Laminated mudstone and sandstone (LF4)	<i>Ophiomorpha-Chondrites-Phycosiphon</i> , <i>Thalassinoides-Planolites</i> , and <i>Phycosiphon</i> dominated.	1 to 60%	15.3 (7) 9.2 to 19.8	6.7 (7) 1 to 41.51	16.8 (Sample 5) 4.9 (Sample 4)	45.71 (Sample 5) 11.06 (Sample 4)
Event-bed deposition	Bioclastic horizon (LF3)	Spreiten burrow.	1 to 5%	10.6 (9) 2.4 to 18.8	28.3 (9) <0.1 to 208	Not sampled	Not sampled
	Massive to low-angle bedded sandstone (LF2)	<i>Ophiomorpha-Chondrites-Phycosiphon</i> .	60 to 90%	21.7 (7) 18.3 to 24.1	245.2 (7) 54.1 to 561	Not sampled	Not sampled
Fairweather deposition	Bioturbated sandstone with common shell material (LF1)	<i>Ophiomorpha</i> dominated, <i>Ophiomorpha-Phycosiphon</i> , and burrow mottled.	60 to >90%	16.4 (12) 12 to 22.7	73.1 (12) 0.1 to 376	23.4 (Sample 3) 27.2 (Sample 2) 20.3 (Sample 1)	18.33 (Sample 3) 9.32 (Sample 2) 79.36 (Sample 1)

\*Core-plug data porosity and permeability measurements (mean, number of samples, range) (Core Laboratories Canada Ltd., 1999), with comparable core-slab sample probe-permeameter measurements (TEMCO Inc. MP-401) and porosity measurements from Digital Image Analysis (Simple PCI®).

(0.11–0.19-in.) thickness were removed from the core-slab face of each sample; one for preparation of a large thin slice to study lithological contrasts between burrows and host matrix (see Garton and McIlroy, 2006), and another slice to make blue epoxy-impregnated thin sections to visually estimate porosity and sorting. The core-slab surface was divided into a grid (Dreyer et al., 1990), and spot-permeability data were obtained using a steady-state probe permeameter (TEMCO Inc. MP-401). Porosity measurements are unstressed (e.g., in ambient laboratory conditions, not at calculated reservoir confining stresses), and permeabilities are unstressed horizontal air permeabilities.

### Thin-Section Analysis

Thin sections (2.5 × 4.5 cm [0.9 × 1.7 in.]) were cut from a slice of the core-slab face. The sample was then impregnated with blue epoxy resin to highlight pore spaces when viewed under the microscope (see Figures 2, 3). Visual estimates of sorting

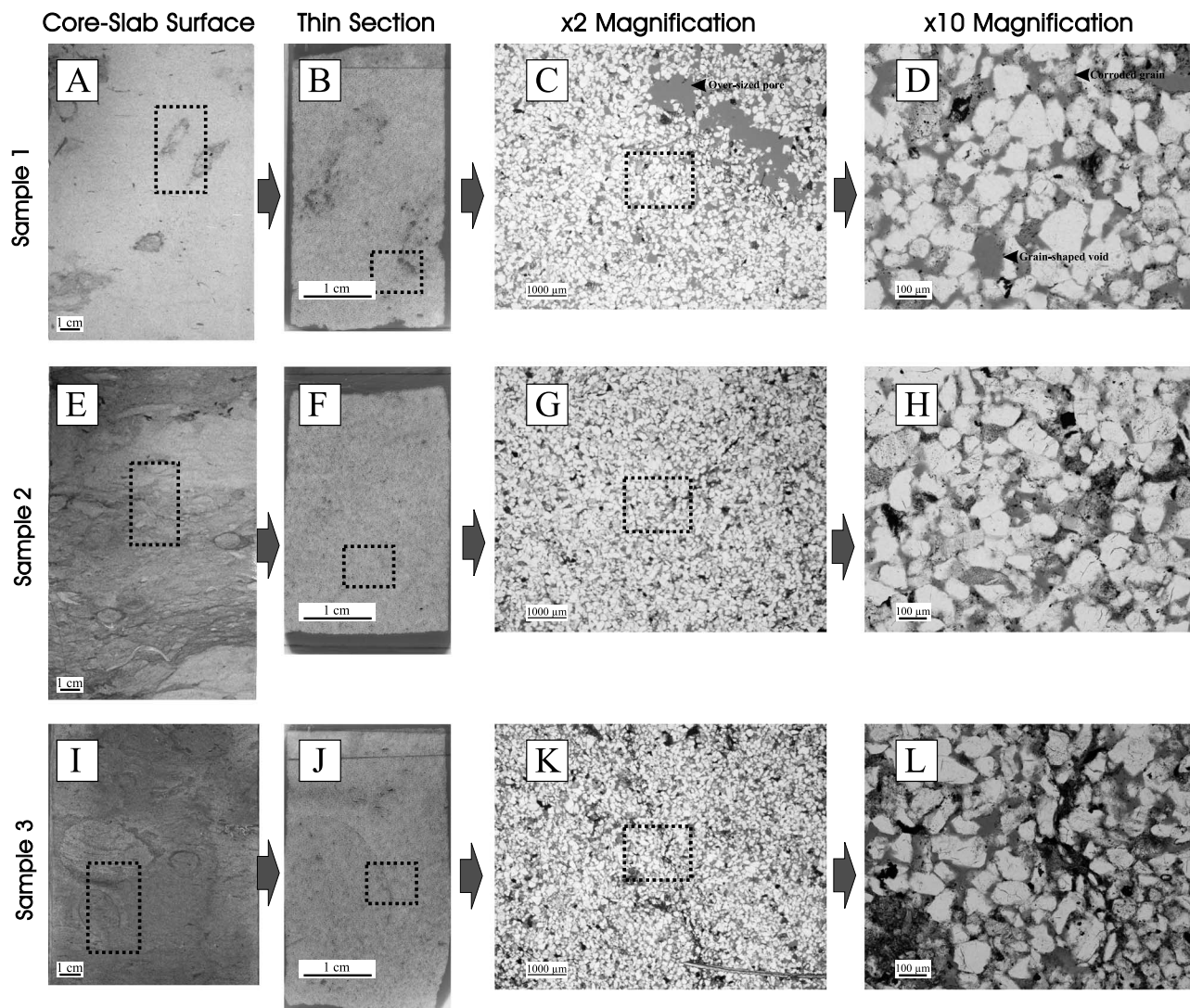
were measured using comparison charts (Jerram, 2001). A digital image analysis software (Simple PCI®) is used to calculate the relative proportions of blue pore space in a given area of interest, and this two-dimensional (2-D) visual measurement is taken as a proxy for the corresponding porosity.

### Large Thin Slicing

The technique of large thin slicing is used to study the sedimentary and biogenic fabrics in sandstone and mudstone lithologies in transmitted light (Garton and McIlroy, 2006). When viewed in transmitted light, the large thin slices display sedimentary structures and detailed ichnology not otherwise visible in polished hand specimens or field samples (Figures 4, 5).

### Probe Permeameter Measurement

The probe permeameter (TEMCO Inc. MP-401) injects compressed nitrogen gas into the rock and,

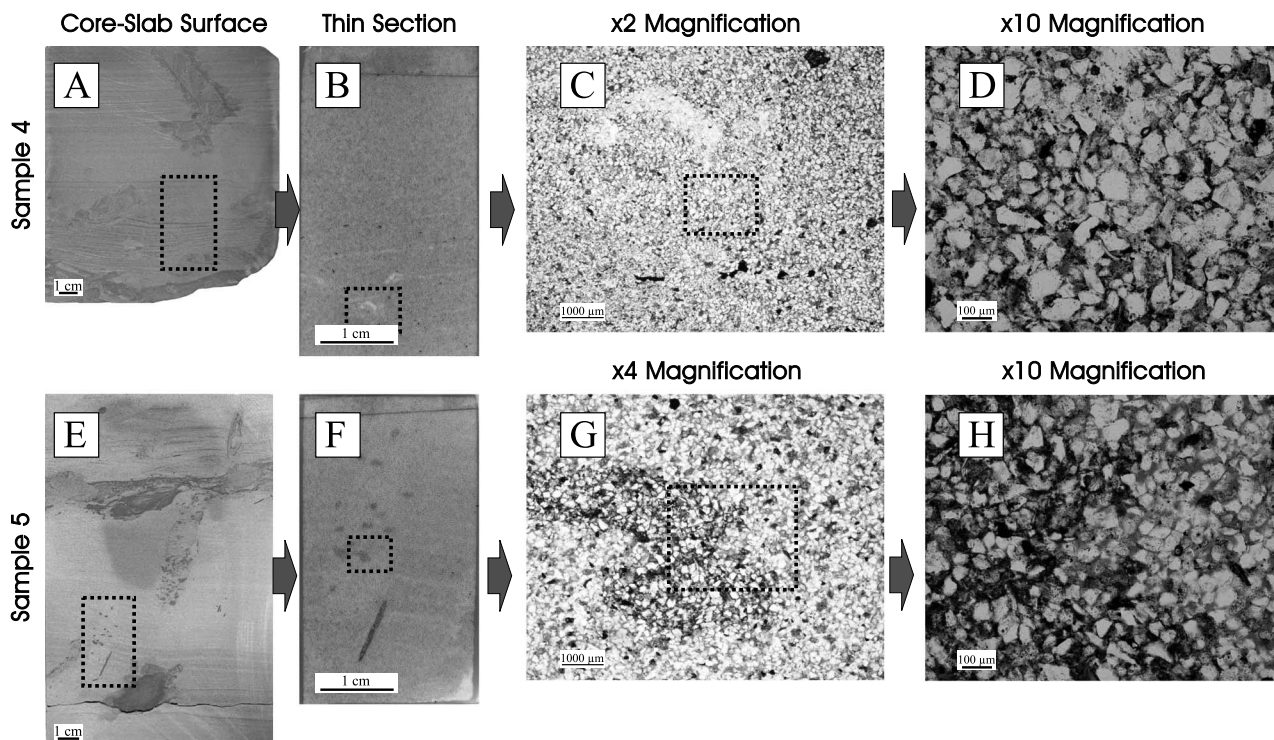


**Figure 2.** Porosity and petrographic details of samples 1, 2, and 3 from bioturbated sandstone lithofacies 1 (LF1) taken from the Ben Nevis L-55 core-slab interval of 2475 to 2388 m (8120 to 7835 ft). Thin sections (B–D, F–H, and J–L) are impregnated with blue epoxy, gray shows pore space, off-white are quartz grains, and dark colors are organic matter, clay minerals, or pyrite. Dashed black rectangles in panels A, E, and I delineate where thin-section samples were taken, and dashed black boxes in panels B, C, F, G, J, and K delineate where plane-polarized light photomicrographs were taken. (A) Core-slab sample 1 (2475 m [8120 ft]) with intense bioturbation (>90%) and *Ophiomorpha* burrows. (B) Oversized pores are concentrated at *Ophiomorpha* burrow margins. (C) Close-up of large gray oversized pores. (D) Interparticle porosity (gray), corroded grains, and grain-shaped voids. Sample porosity is 20.3%. (E) Core-slab sample 2 (2460 m [8071 ft]) with intense bioturbation (>90%) and *Ophiomorpha* burrows. (F) Burrow-mottled texture. (G) Quartz-rich very fine sandstone. (H) Interparticle porosity (gray) and pore-filling clay minerals. Sample porosity is 27.2%. (I) Core-slab sample 3 (2388 m [7835 ft]) with intense bioturbation (>90%), *Ophiomorpha* and *Thalassinoides*. (J) Clean sand *Thalassinoides* burrow halo and mudstone-rich *Ophiomorpha* burrow lining. (K) Close-up of *Thalassinoides* burrow margin. (L) Interparticle porosity (gray), clay overgrowths, and pore-filling clay minerals concentrated in burrow lining. Sample porosity is 23.4%.

using a tip of 3.18–6.35-mm (0.12–0.25-in.) inner-outer diameter, measures the flow rate and injection pressure in a rock volume of approximately 1 cm<sup>3</sup> (0.06 in.<sup>3</sup>). Permeability in millidarcies was calculated using the appropriate form of Darcy's equation modified by the half-space solution of a geo-

metrical factor  $G_0$  as a function of probe-tip seal thickness (Goggin et al., 1988). In each of the five center-cut core-slab samples, a 1-cm (0.3-in.) grid was drawn on the surface, and spot-permeability measurements were taken in the center of each square (Table 1). Four measurements were taken





**Figure 3.** Porosity and petrographic details of samples 4 and 5 from bioturbated mud-rich very fine sandstones lithofacies 4 (LF4) taken from the Ben Nevis L-55 core-slab interval of 2357 to 2356 m (7733 to 7730 ft). Thin sections (B–D, F–H) are impregnated with blue epoxy, gray shows pore-space, off-white are quartz grains, and dark colors are organic matter, clay minerals, and pyrite. Dashed black rectangles in panels A and E delineate where thin-section samples were taken, and dashed black boxes in panels B, C, F, and G delineate where plane-polarized light photomicrographs were taken. (A) Core-slab sample 4 (2357 m [7733 ft]) with low bioturbation (5–30%), vertically oriented *Ophiomorpha* burrow, and laminations. (B) Diffuse laminations and indistinct burrow. (C) Close-up of clay-rich burrow lining. (D) Interparticle porosity (gray) and pore-filling clay, calcite, and clay cements occluding available pore space. Sample porosity is 4.9%. (E) Core-slab sample 5 (2356 m [7730 ft]) with moderate bioturbation (30–60%), *Ophiomorpha* burrow, *Chondrites* burrows, and laminae. (F) Mudstone-filled *Chondrites* burrows in mud-rich, diffusely laminated very fine sandstone. (G) Close-up of *Chondrites*. (H) Interparticle porosity (gray) and pore-filling clay minerals in *Chondrites* burrow. Sample porosity is 16.8%.

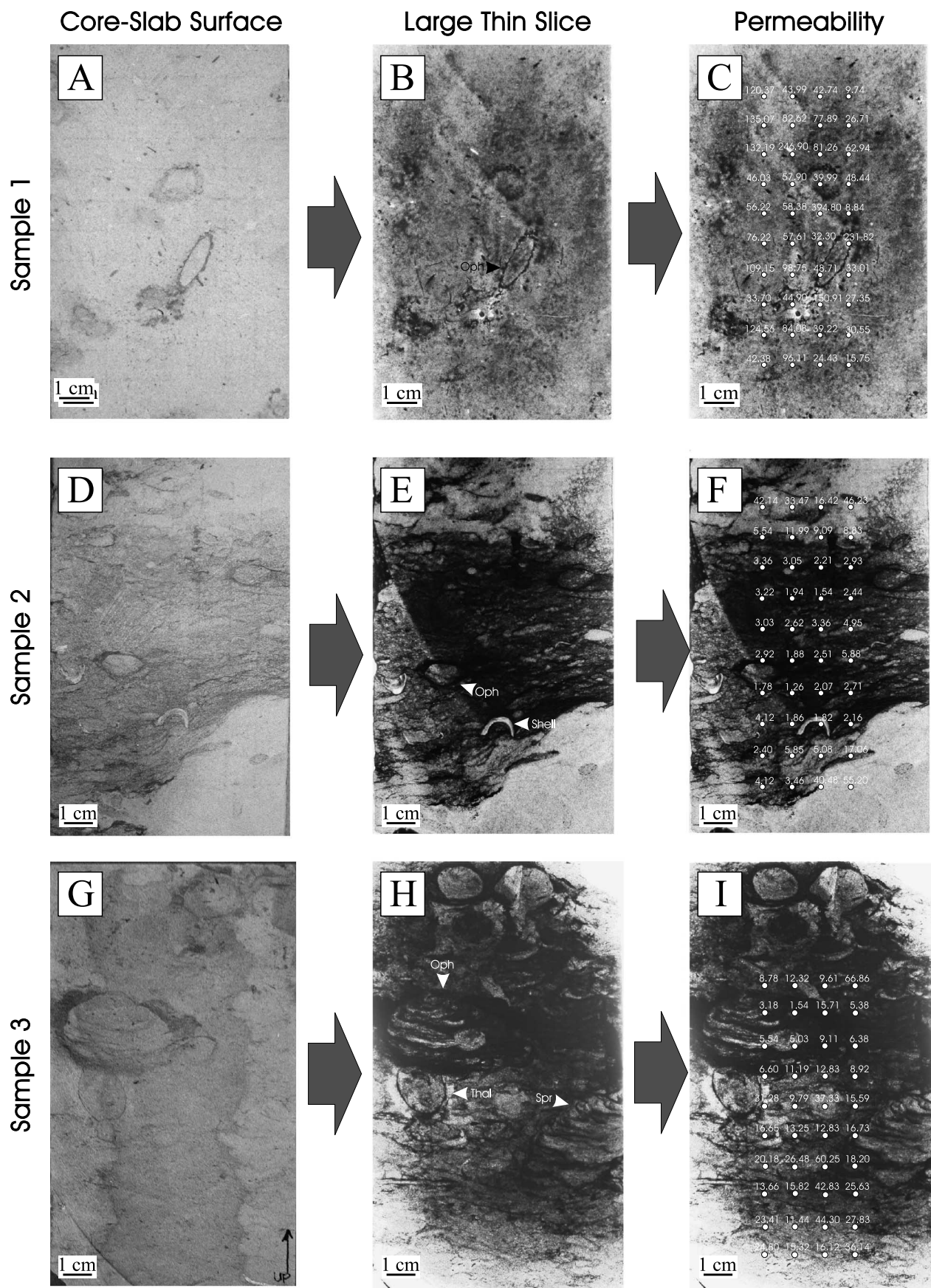
for each of 40 points on the grid to obtain an average (Figures 4C, F, I; 5C, F).

## SEDIMENTOLOGY AND ICHNOLOGY OF BEN NEVIS L-55

### Sedimentology of Ben Nevis L-55

The Ben Nevis Formation in the L-55 well displays a net upward-fining trend, with mudstone content increasing upward. The cored interval is dominated by bioturbated fine grained sandstones with shell lags and mudstone beds grading into mud-rich very fine sandstone at the top of the cored interval (Table 1). Mudstone laminae, low-angle stratification, dispersed shell fragments (decreasing up-

ward), bioclastic beds, and carbonaceous material are common throughout, along with rare mudstone rip-up clasts and sideritized mudstone clasts. Five lithofacies (LF) are defined herein: LF1, bioturbated sandstone with shell material; LF2, low-angle cross-stratified sandstones; LF3, bioclastic sandstones; LF4, laminated very fine grained sandstones with mudstone; and LF5, bioturbated sandy mudstones (see Table 1; Figure 6). Lithofacies 1 and 5 are intensely bioturbated and contain disseminated carbonaceous matter and shell debris. Bioturbation intensity in LF1 and LF5 ranges between 60 and 100% but is typically about 75%. Lithofacies 2, 3, and 4 are sparsely to moderately bioturbated (1–60%). Intensely bioturbated facies LF1 and LF5 are interpreted as fair-weather beds (Figure 6A, B). Less intensely bioturbated sandstone and mudstone





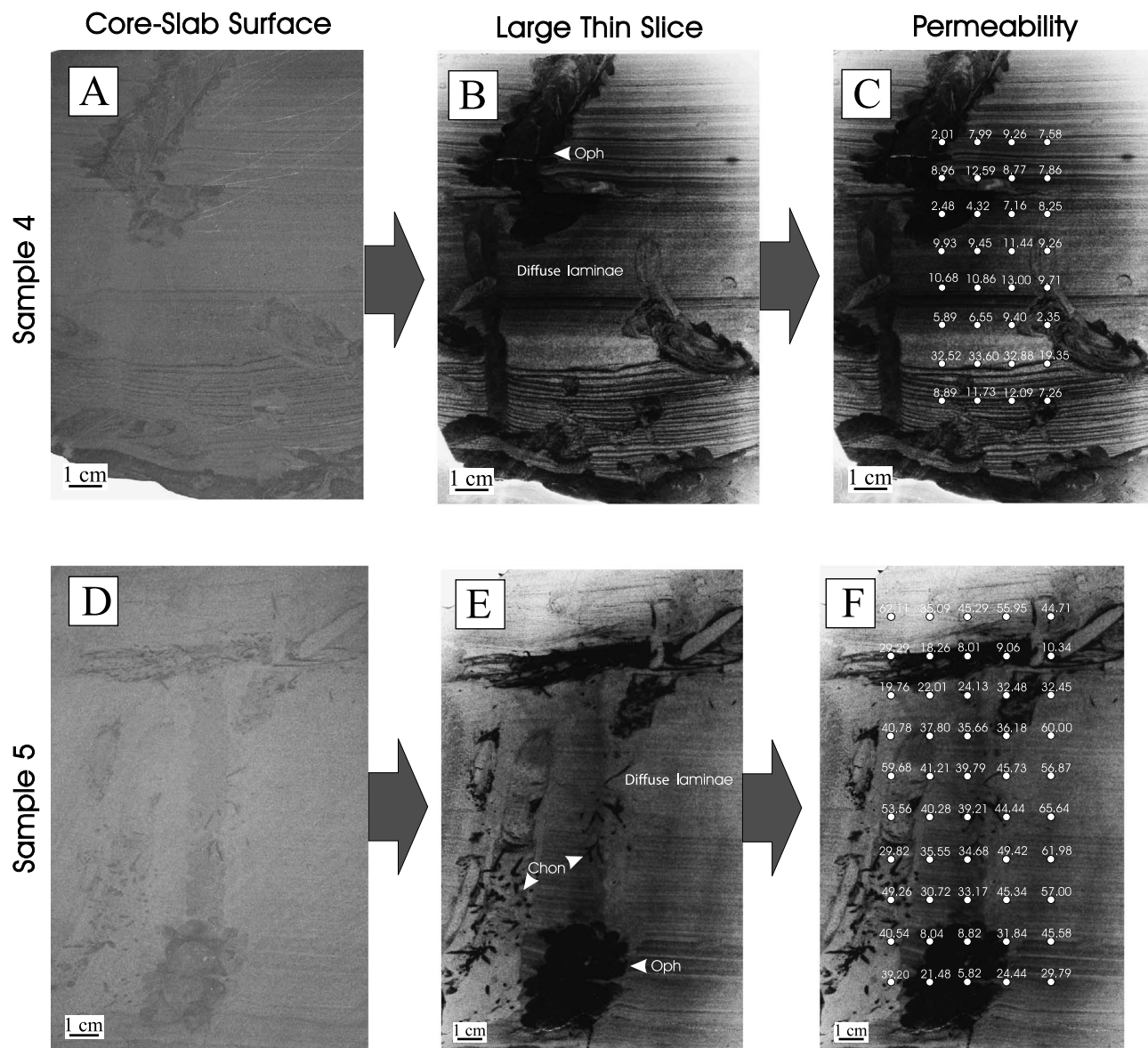
units are interpreted to be event beds deposited during periods of intense hydrodynamic activity in which bioturbation is exclusively post-depositional (cf. Aigner, 1985).

The dominant facies in the cored interval is LF1, highly bioturbated sandstones that contain dispersed shelly debris. The presence of coarse shelly lags (LF3) and pebble horizons at the base of bioturbated units suggests event-bed deposition followed by bioturbation during protracted periods of low hydrodynamic energy. Lithofacies 2 consists of fine-grained, low-angle, cross-laminated sandstones that are either unbioturbated or contain low to moderate levels of bioturbation (5–60% bioturbation; Figure 6C). The cross laminae are considered to be either storm-induced hummocky cross-stratification (Dumas and Arnott, 2006) or suspension settling in mouth-bar settings (cf. Brett et al., 2002). Sections of laminated sandstone (LF2 and 4) show diffuse zones that may have formed biogenically by meiofaunal cryptobioturbation (see Howard and Frey, 1975) or by small-scale physically induced dewatering or liquefaction (Figure 6C) (Owen, 1996; Hildebrandt and Egenhoff, 2007). We consider it to be nearly impossible to distinguish between these possibilities for lack of objective recognition criteria. The bioclastic beds of LF3 comprise abundant broken, current-sorted bivalves (especially oysters), along with gastropods and serpulid worm tube segments (Figure 6D). The shell beds of LF3 are also commonly interbedded with LF1, either as erosively based shell lags below sandstone beds or as up to 20-cm (8-in.)-thick bioclastic beds with low sand content. The laminated sandstone and mudstone beds of LF4 are planar or wavy bedded, or diffusely laminated with partings defined by mud drapes. A basal mudstone-pebble lag, locally with oblate commonly sideritized, mudstone

clasts, and/or shell debris may be present. Alternations of planar laminae, diffuse laminae, and structureless intervals in LF4 are interpreted as periods of variable sedimentation rates. Laminated mudstone beds (LF4) are commonly found to directly overlie cross-stratified sandstone (LF2) in the upper section of core interval. These mudstone beds are interpreted to represent rapid postevent-bed deposition in paleoenvironments with low hydrodynamic energy. The sandy mudstone (LF5) contains the most intense and diverse levels of bioturbation within the cored interval (Figure 6E). This highly bioturbated facies (LF5) is commonly intercalated with laminated horizons (LF4) and can be referred to as a “lam-scam” style of deposition (Howard, 1972). Laminated beds are deposited under high-flow regime conditions, for example, during storm events, followed by scrambling of the sediment by bioturbation during low-energy post-event periods (Ekdale et al., 1984). Coalified and pyritized wood clasts are common in all facies and may indicate proximity to a distributary system and/or transgressive reworking and erosion of the plant-rich Gambo Member (Sinclair, 1993).

The heterolithic nature of that part of the Ben Nevis Formation cored at L55 is consistent with event-bed deposition in an offshore setting. Event beds are thought to be storm induced with evidence for fluvial influence on the system in the form of fluid-mud deposits and plant debris. Toward the top of the Ben Nevis succession in the L-55 core, the mudstone-rich facies (LF5) becomes dominant, and this is taken to reflect an increase in relative sea level (Figure 6F, G). In summary, deposition of the facies represented in the cored interval of Ben Nevis L-55 is thought to have occurred on a wave-dominated coastline with some fluvial influence. No back-barrier or lagoonal facies were identified. The depositional

**Figure 4.** Large thin slices and permeability data of samples 1, 2, and 3 from bioturbated fine sandstone (LF1), assigned an *Ophiomorpha*-dominated ichnofabric from the Ben Nevis L-55 core interval of 2475 to 2388 m (8120 to 7835 ft). Core-slab slices (A, D and G) and large thin slice images (B, E, and H) with spot-permeability measurements overlain (C, F, and I). (A) Core-slab sample 1 (2475 m [8120 ft]). (B) *Ophiomorpha* (Oph) margins and concentrations of clay-filled pores of burrow-mottled sandstone. (C) Permeability data points range from 8.84 to 394.80 md. (D) Core-slab sample 2 (2460 m [8071 ft]) of bioturbated fine sandstone with shell fragments. (E) Burrow-mottled mud-rich sandstone and clean sandstone bed at base. (F) Permeability data points range from 1.26 to 55.20 md. (G) Core-slab sample 3 (2388 m [7835 ft]). (H) *Thalassinoides* (Thal) burrow halo, mud-pellet lined *Ophiomorpha*, and spreiten burrow (Spr). (I) Permeability data points range from 1.54 to 66.86 md.



**Figure 5.** Large thin slices and permeability data of samples 4 and 5 from bioturbated laminated mud-rich very fine sandstone (LF4), assigned an *Ophiomorpha-Chondrites-Phycosiphon* ichnofabric from the Ben Nevis L-55 core interval of 2357 to 2356 m (7733 to 7730 ft). Core-slab slices (A and D) and large thin-slice images (B and E) with spot-permeability measurements overlain (C and F). (A) Core-slab sample 4 (2357 m [7733 ft]). (B) Discrete *Ophiomorpha* (Oph) and indeterminate traces crosscutting distinct and diffuse laminae. (C) Permeability data points range from 2.01 to 33.60 md. (D) Core-slab sample 5 (2356 m [7730 ft]). (E) *Chondrites* (Chon) burrows and pyritized *Ophiomorpha* burrows in diffusely laminated host sediment. (F) Permeability data points range from 5.82 to 65.64 md.

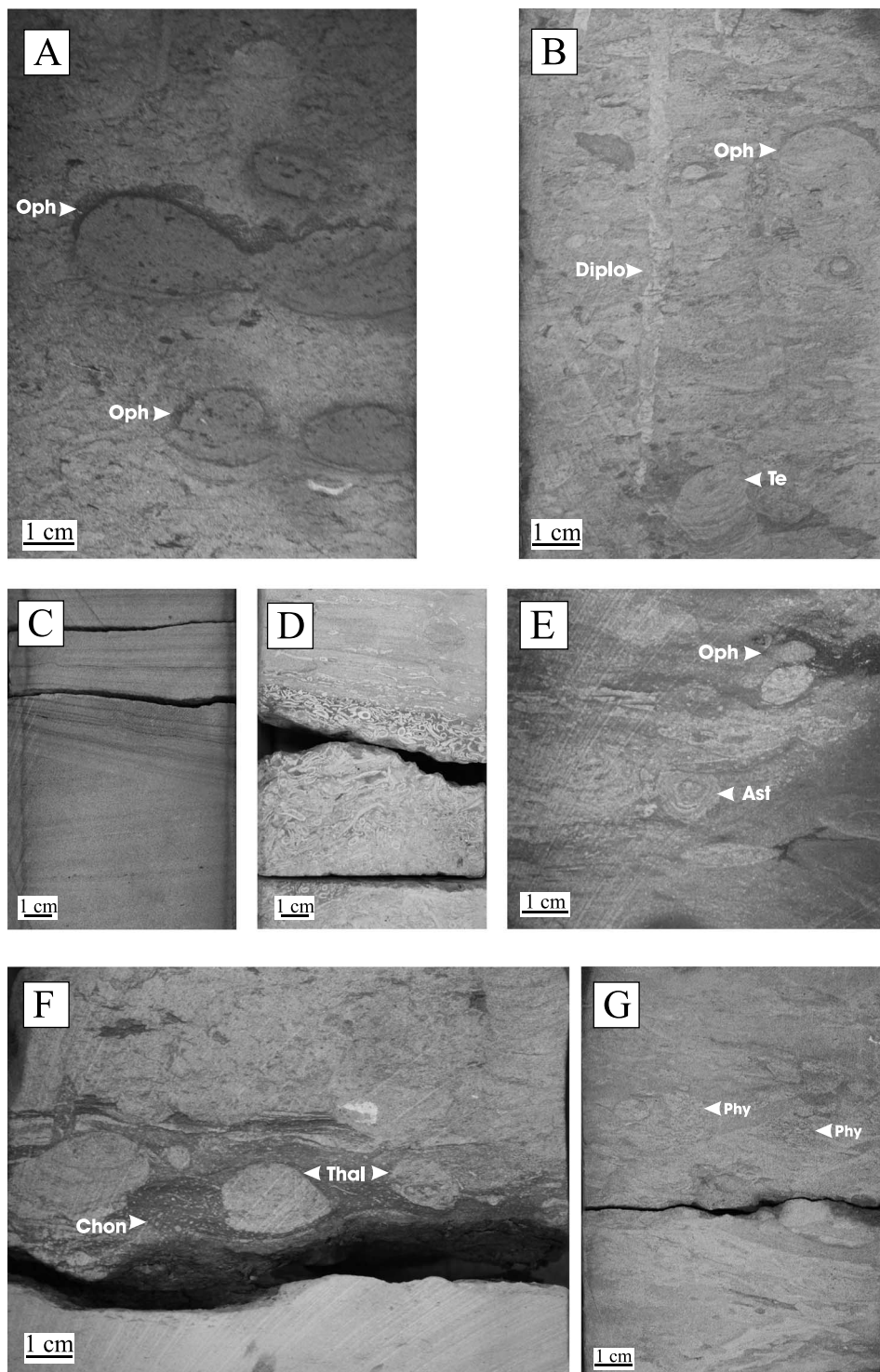
setting is perhaps best compared to that of a wave-dominated delta.

### Ichnology of Ben Nevis L-55

A diverse assemblage of deposit- and suspension-feeding marine trace fossils are found in the cored interval. Ichnotaxa include (by first occurrence at base of core) *Ophiomorpha*, *Phycosiphon*, *Thalassi-*

*noides*, *Planolites*, *Chondrites*, *Diplocraterion*, *Teichichnus*, *Palaeophycus*, and *Asterosoma* (Figure 6). Indistinct burrow mottling is also present throughout the core. Bioturbation intensity is extremely variable and is found to be facies dependent (Table 1). Measurement of the common trace fossils shows that burrow diameters of *Ophiomorpha*, *Thalassinoides*, and *Asterosoma* remain constant throughout the succession. This suggests that they were created





**Figure 6.** (A) *Ophiomorpha* (Oph)-dominated ichnofabric in lithofacies 1 (LF1); note irregular mud pellets on the roof of the *Ophiomorpha irregulaire* burrow only. (B) *Ophiomorpha*-dominated ichnofabric with *Diplocraterion* (Diplo) and *Teichichnus* (Te) burrows in lithofacies 1 (LF1). (C) Low-angle cross-stratified sandstone lithofacies 2 (LF2). (D) Oyster- and calcareous-worm-tube-rich bioclastic horizon of lithofacies 3 (LF3). (E) *Ophiomorpha*-*Asterosoma* ichnofabric in upper sandy mudstone lithofacies 5 (LF5), *Asterosoma* (Ast). (F) *Thalassinoides* (Thal) and *Chondrites* (Chon) in laminated mudstone facies 4 (LF4) with *Thalassinoides*-*Planolites* ichnofabric, interbedded with bioturbated sandstone with shell material lithofacies 1 (LF1). (G) Clusters of mudstone-filled *Phycosiphon* burrows with sandy haloes in *Phycosiphon*-dominated ichnofabric of lithofacies 4 (LF4).

by adult organisms, probably in an equable paleo-environmental setting. Rare escape traces exist and are associated with event beds; they are likely a result of organism entrainment during event-bed flow and transport (cf. Follmi and Grimm, 1990).

*Ophiomorpha* (5–50-mm [0.19–1.9-in.] diameter) is the most abundant and conspicuous trace fossil in the succession; visually dominates most of the described ichnofabrics in the lower part of the L-55 core; and is an accessory component of

ichnofabrics in many of the mudstone-rich beds at the top of the Ben Nevis Formation. *Ophiomorpha* burrows are lined with circular to oval mudstone or organic-detritus-rich pellets. In several cases, the pellets are only present on the roof of the burrow. Burrow fill is lithologically variable and may comprise either a massive sandstone infill or a concentrically laminated mudstone fill (Figures 2A–D; 3E; 6A, B, E, F). The three-dimensional (3-D) morphology of *Ophiomorpha* galleries are known to include boxworks, networks, and mazes (Frey et al., 1978). Many modern species of burrowing (*Ophiomorpha* and *Thalassinoides* producing) crustaceans produce interconnected burrow networks (Pryor, 1975). Analogous fossil burrow systems thus have the potential to produce enhanced permeability fabrics within sedimentary successions (see Figures 4, 5), although burrows with similar cross-sectional expressions may comprise isolated shafts and tunnels (e.g., Miller and Curran, 2001). This uncertainty regarding the degree to which the fossil burrows *Thalassinoides* and *Ophiomorpha* are in horizontal communication, and the macropore networks that they form, remains a problematic issue in some hydrocarbon reservoirs (Gingras et al., 2007).

Unlined *Thalassinoides* burrows (10–21-mm [0.3–0.8-in.] diameter) are common in Ben Nevis L-55 but are only clearly visible in mudstone-rich laminated beds (LF4) and sandy mudstone (LF5) (Figure 6F). Large thin slices created using the method of Garton and McLroy (2006) reveal that *Thalassinoides* is actually present in all facies throughout the core (compare Figure 4G, I). The fill of *Thalassinoides* burrows is commonly found to correspond to that of the lithology of the overlying colonization surface (Figure 6F). This is generally taken to indicate that the burrow was created as an open burrow and kept open with self-induced water currents (Sheehan and Schiefelbein, 1984). Modern thalassinid shrimps construct burrows that resemble *Thalassinoides* trace fossils with vertical shafts and horizontal to oblique galleries at depths of up to 1 m (3 ft) (Sheehan and Schiefelbein, 1984; Swinbanks and Luternauer, 1987). Sandstone-filled *Thalassinoides* create vertical and horizontal macropore networks in Ben Nevis L-55 with the potential

to act as flow conduits in hydrocarbon reservoirs, but, as is the case with *Ophiomorpha*, isolated burrows may require mechanical fracturing in the horizontal plane to create reservoir flow units.

Mudstone-filled burrows of *Phycosiphon* (<1-mm [0.03-in.] diameter; Wetzel and Bromley, 1994) and *Chondrites* (1–2-mm [0.03–0.07-in.] diameter; Bromley and Ekdale, 1984) are common throughout the core interval (Figure 6F, G) with the exception of the bioclastic horizons (LF3). Clusters of the trace fossils are generally horizontal or oblique and may overprint other traces such as *Ophiomorpha*. In clusters, these trace fossils may create localized low-porosity patches in the host sediment.

Burrow mottling is persistent throughout the Ben Nevis L-55 core (Figures 4, 6) and is commonly crosscut by discrete burrows. These undeterminable biogenic structures are associated with repeated overprinting in horizons with intense bioturbation (>90%). This burrow-mottled texture is interpreted to reflect burrow homogenization of the primary sedimentary fabric and may create zones of permeability enhancement relative to the host sediment (Meyer and Krause, 2006).

### **Bioturbation and Ichnofabric in Ben Nevis L-55**

Event-bed preservation (e.g., LF2, 3, 4) is a function of sedimentation rate, biogenic mixing rate, and event-bed thickness (Wheatcroft, 1990; Bentley and Sheremet, 2003). In this study, event beds with low-angle cross-stratification, greater than around 10 cm (3.9 in.) in thickness, are found to greatly suppress bioturbation. Densely packed bioclastic beds are also generally found to be unbioturbated (Figure 6D).

Tiering of traces within the Ben Nevis Formation event beds includes rarely preserved shallow tier trace fossils such as *Diplocraterion*, perhaps by instantaneous casting (cf. Einsele and Seilacher, 1991) (Figure 6B). In facies that are interpreted to represent slow continuous deposition (e.g., LF1 and LF5), evidence for repeated overprinting can be recognized. Colonization order-of-trace makers is difficult to determine because very few crosscutting relationships are recognized. Nonetheless, *Diplocraterion* is seen cutting *Ophiomorpha*, *Phycosiphon*



traces are overprinting *Ophiomorpha* burrows, and all burrows crosscut indistinct burrow-mottled ichnofabric. Shallow tier burrows are poorly preserved, and the ichnofabric is dominated by mid to deep tier trace fossils (e.g., *Ophiomorpha*, *Thalassinoides*, *Phycosiphon*, and *Chondrites*; cf. Bromley, 1990).

Nine discrete ichnofabrics (Table 1) have been recognized in Ben Nevis L-55 and have been categorized into either intensely bioturbated fair-weather or event-bed-related ichnofabric associations sensu McIlroy (2007). Ichnofabrics characterizing the fair-weather ichnofabric association (associated with bioturbated sandstone and mudstone, LF1 and LF5) are typically *Ophiomorpha* dominated. Fair-weather ichnofabrics include the *Ophiomorpha-Phycosiphon*, *Ophiomorpha-Asterosoma*, *Teichichnus-Phycosiphon*, and burrow-mottled ichnofabrics. The event-bed-related ichnofabrics are *Ophiomorpha-Chondrites-Phycosiphon* (associated with laminated sandstone, LF4, and the low-angle cross-stratified sandstone LF2); spreiten-burrow ichnofabric, associated with the bioclastic (LF3); *Thalassinoides-Planolites*; and the *Phycosiphon*-dominated ichnofabric of the laminated mudstone facies (LF4).

Core-slab samples 1, 2, and 3 are of the *Ophiomorpha*-dominated fair-weather ichnofabric in the bioturbated sandstone facies (LF1; Figures 2, 4). Samples 4 and 5 come from the laminated sandstone facies (LF4; Figures 3, 5) and contain the *Ophiomorpha-Chondrites-Phycosiphon* event-bed ichnofabric. On the basis of data presented, these two ichnofabrics are associated with improved reservoir quality in the Ben Nevis L-55 well. Detailed assessment of the host sediment has been undertaken to fully understand the impact of bioturbation on reservoir quality.

## Porosity and Permeability in Ben Nevis L-55

The main controls on spot-permeability contrasts are lithology and cementation, a simple and expected relationship between higher permeability sandstone and lower permeability mudstone, muddy sandstone, or cemented zones. Processes that affect the distribution of grain-size fractions are the development of physical and biogenic structures. In the Ben Nevis L-55 core, mudstone-rich facies

(LF4) and ichnofabrics containing mudstone-filled and/or lined burrows (e.g., *Ophiomorpha* and clusters of *Chondrites*) have the net effect of permeability reduction. In contrast, sandstone-rich facies (LF1 and LF2) with sandstone-filled burrows (e.g., *Thalassinoides*) and ichnofabrics with burrow-mottled or diffuse to massive textures have the net effect of permeability enhancement.

The main pore type is intergranular porosity, which has been reduced by pore-filling detrital clay, bioclasts, calcite cements, and sedimentary lithoclasts. Thin-section analysis reveals grain-size sorting associated with sedimentary structures (e.g., laminae) and biogenic structures (trace fossils). Concentration of the clay-silt grade material into laminae, burrow linings, and fill (e.g., *Ophiomorpha* and *Chondrites*; see Figures 3, 5) within sandstone decreases sorting of grains and therefore reduces porosity. The biogenic process can be described as sediment packing. Conversely, mud-lined burrows (e.g., *Thalassinoides*) create zones of biologically cleaned sandstone, as mud and organic matter are preferentially removed from host sediment (23.4% and 31.28 md; see Figures 2I–L, 4I). Sorting and concomitant increased porosity are created by the process of sediment cleaning in these burrows. Burrow-mottled fabrics or diffuse to massive horizons are formed by the biogenic process of sediment mixing.

Anomalous permeability data points on large thin-slice images that do not appear to be directly associated with any sedimentary or biogenic features on the slabbed surface are suggested to be influenced by high-permeability domains (e.g., burrows and dissolution voids) or low-permeability zones (shells and pyrite) in the core that do not cut the 2-D surface (see Figures 4C, 5F). In this regard, remember that the probe permeameter reflects a 3-D sample volume, which is only partially represented by slabbed surfaces.

## HOST SEDIMENT POROSITY AND PERMEABILITY IN BEN NEVIS L55

All samples are predominantly fine to mud-rich very fine grained sandstones. Sandstone composition is dominated by quartz grains, with lesser amounts of

feldspar, calcite, lithic clasts, clay, and organic detritus. Good interparticle (primary) porosity is present between moderate to well-sorted, subangular to subrounded loosely packed grains (Figures 2, 3). Porosity measured from blue-epoxy-impregnated thin sections is between 4.9 and 27.2%. We suggest that the intergranular pore space was preserved due to early calcite cementation, followed by subsequent dissolution of pore-filling cements (Hesse and Abid, 1998). The source of the early calcite cementation in the Ben Nevis Formation is through dissolution of bioclastic material from within the reservoir interval (Hesse and Abid, 1998). Secondary porosity can be recognized in the form of oversized pores, corroded grains, floating grains, and grain-shaped voids in the sandstone (Figure 2D, H, L). This suggests that the secondary porosity is generated from dissolution of shell fragments, calcite cement, lithic clasts, clay minerals, and feldspar grains.

Physical sedimentary structures are absent in samples 1, 2, and 3 from the bioturbated fine sandstone facies (LF1) as a result of the intense bioturbation. High-permeability values in sample 1 are found in clean, mud-deficient sandstone-rich areas (Figure 4C). Lower permeability regions of samples 2 and 3 correspond to mud-rich bioturbated sandstone with shell fragments (Figure 5C, F). Samples within this facies preserve no original depositional fabric, only burrow mottling with few discrete burrows visible. Samples 4 and 5 of the laminated sandstone facies (LF4) generally have well-developed very fine (<1–3 mm [0.03–0.11 in.]) planar and parallel mudstone laminae within very fine sandstone. The porosity and permeability of the host sediment are low because of well-developed closely spaced mudstone laminae. The higher permeability data points of sample 5 are a result of lower mud content in the laminated sandstone and greater proportions of diffusely laminated to massive texture (Figure 5F).

## BIOTURBATED SEDIMENT POROSITY AND PERMEABILITY IN BEN NEVIS L-55

Burrowing organisms can secrete mucus as they move through the sediment; use mucus to trap or-

ganic matter or fine grains; or incorporate detritus (mud or sand) to create a burrow wall or lining (Bromley, 1990). Consequently, burrows can alter the geochemistry of a substrate, acting as focal points for the colonization of microbes and mineralization, which may consequently drive early diagenetic processes (Bromley, 1990; Pemberton and Gingras, 2005). This biogeochemical reaction may promote burrow-induced diagenesis, with pyrite (Figure 5E), siderite, and calcite growth centered on the burrow (Pemberton and Gingras, 2005; Gingras et al., 2007).

In highly bioturbated ichnofabrics from LF1 (Figures 2, 4), discrete traces are generally not preserved as a result of repeated overprinting. Samples 1, 2, and 3 of this facies preserve no original sedimentary fabric and are categorized as burrow mottled. Porosity and permeability within the burrow-mottled sandstone are enhanced relative to unbioturbated sandstone by one or both of two animal-sediment interactions: (1) sediment packing, the removal of silt-clay-grade material from the host sediment, and redepositing it in burrow linings and fills; and (2) sediment cleaning, the removal of silt-clay-grade material from the sedimentary environment (i.e., back to the sediment-water interface). Incorporation of silt-clay-grade material from the host sediment into burrow fills and/or linings creates only localized, discontinuous areas of reduced porosity and permeability (Figure 4) due to the silt-clay-size fraction-filling pore space. The removal of silt-clay-grade material from the host sediment by deposit-feeding organisms that defecate at the overlying sediment-water interface can create areas of biologically enhanced porosity and permeability within burrows. Both of these biological processes generally improve the porosity and permeability characteristics of the sediment. The results are consistent with Meyer and Krause (2006) who documented higher and relatively isotropic directional permeabilities in bioturbated middle shoreface sandstones relative to unbioturbated, laminated sandstones.

Our petrographic analyses demonstrate that the *Ophiomorpha*-producing organism(s) create localized zones of porosity reduction (along burrow walls), and the *Thalassinoides* trace maker creates

porosity enhancement, relative to the host sediment within the reservoir (see Figure 2I–L). Corresponding spot-permeability measurements also display similar trends (Figure 4G–I).

### **Porosity and Permeability of *Ophiomorpha*-Dominated Ichnofabric**

This ichnofabric is dominated by conspicuous *Ophiomorpha* burrows within burrow-mottled fine sandstones from the bioturbated fine sandstone facies (LF1). Samples 1, 2, and 3 are representative of the *Ophiomorpha*-dominated ichnofabric. The porosity estimate for sample 1 is 20.3%, that of sample 2 is 27.2%, and that of sample 3 is 23.4% (Figure 2). Permeability ranges recorded from this facies range from 1.26 to 394.80 md. The highest permeability values are from sample 1 averaging 79.36 md (Figure 4C), with samples 2 and 3 averaging 9.32 and 18.33 md, respectively (Figure 4F, I). Bioturbation level ranges from 60 to 100%, with discrete burrows, including pellet-lined *Ophiomorpha* and the unlined tubular burrows of *Thalassinoides*. In addition, some undetermined sandstone-filled burrows and an inclined spreiten burrow are only visible in large thin slices (Figure 4G–I). Sandstone-rich zones are characterized by higher permeability zones (8.84–394.80 md; Figure 4C) than the mudstone-rich burrow-mottled zones (1.26–66.86 md; Figure 4F, I).

*Ophiomorpha* burrow fills, margins, and linings have clay-rich pores relative to the surrounding clean high-porosity sandstone. Permeability data support this observation, with spot-permeability data points within *Ophiomorpha* burrows and at the burrow margins being low (e.g., 1.54–15.71 md), relative to the surrounding higher permeability (5.38–66.86 md) sandstone (Figures 4I). In one of the studied specimens, oversized pores are present within *Ophiomorpha* burrow margins (see Figure 2A–D). These are inferred to have formed by dissolution of burrow lining during secondary porosity development (Figure 4C). Thin-section samples were impregnated with blue epoxy prior to preparation to prevent clay disaggregation. *Ophiomorpha* burrows were created by sediment packing during deposit-feeding activity, in which the trace-making organ-

ism concentrates mud and organic-rich particles into burrow linings. The effect of this is to reduce porosity and permeability in the near-burrow environment relative to the biologically cleaned host sediment. The *Ophiomorpha* burrow fill is a passive fill unrelated to the host sediment, which can locally even include ripple cross-lamination. In our material, the burrow fill is typically of low permeability, although we acknowledge that this need not always be the case (Figures 4I, 5F).

*Thalassinoides* burrows studied by us from L-55 are distinguishable as very thin mudstone-lined burrows, with fill similar to, or cleaner than, the enclosing matrix (Figure 2K, L). A halo of high-porosity, clean, well-sorted sandstone is present around a small number of *Thalassinoides* burrows. For example, in sample 3, the *Thalassinoides* burrow is 31.28 md, the adjacent *Ophiomorpha* burrow is 1.54–15.71 md, and the mean permeability for the sample is 18.33 md (Figure 4G–I). This burrow halo exhibits higher porosity and permeability than the matrix (Figure 4I) and may be the result of the trace maker generating a current around its body and expelling fines into the water column (aquarium observations of modern *Neotrypaea californiensis* by McIlroy). At least in the Ben Nevis Formation core of well L-55, *Thalassinoides* is everywhere associated with areas of enhanced porosity and permeability relative to the host sediment.

### **Porosity and Permeability of *Ophiomorpha*-*Chondrites*-*Phycosiphon* Ichnofabric**

This ichnofabric is typically incompletely bioturbated (5–60% bioturbation). The sedimentary fabric is composed of bioturbated mudstone-rich laminae in a very fine grained sandstone matrix (LF4). Pellet-lined *Ophiomorpha* burrows and undetermined sandstone- and mudstone-filled traces are common. Samples 4 and 5 are representative of the *Ophiomorpha*-*Chondrites*-*Phycosiphon* ichnofabric. The porosity of sample 4 is estimated at 4.9% and that of sample 5 is 16.8% (Figure 3). This is significantly lower than the porosities of 20.3, 27.2, and 23.4% from the sandstone-rich samples 1–3 (LF1; Figure 2). The permeability of samples in LF4 ranges from 2.01 to 65.64 md. Sample 4 has a

mean permeability of 11.06 md, and sample 5 has a mean of 45.71 md (Figure 5C, F).

*Ophiomorpha* and *Chondrites* burrows within this ichnofabric are associated with zones of localized porosity and permeability reduction in their mudstone-rich burrow fills and linings (Figures 3, 5). Pellet-lined and filled *Ophiomorpha* burrows significantly reduce permeability (2.01–8.96 md) relative to the host sediment (7.99–12.59 md; Figure 5C). Large opaque zones associated with *Ophiomorpha* burrows are pyritized organic-rich mudstone with low permeability values (8.04–21.48 md) relative to the host sediment (19.76–65.64 md; Figure 5F). Widely spaced mudstone-filled *Chondrites* burrows (1–2-mm [0.03–0.07-in.] diameter) do not affect permeability relative to host sediment (Figure 5F). At the microscale, *Chondrites* significantly reduce porosity relative to the host sediment as silt-clay-grade material is packed into pore space (see Figure 3E–H).

Lamina sets with sharp mud-rich drapes alternate with intervals showing diffuse lamination, interpreted to be formed by cryptobioturbation or liquefaction (Figure 5). Laminae adjacent to burrows are deflected by the vertical movements of bioturbating organisms (Figure 5B). Diffusely laminated lamina sets are characterized by permeabilities between 5.89 and 33.60 md, whereas interlaminated massive sandstone intervals have permeabilities of 7.99–12.59 md (Figure 5C).

## COMPARISON OF CORE-PLUG AND CORE-SLAB POROSITY AND PERMEABILITY

Core-plug porosity values obtained for the sampled facies (LF1 and LF4) of the cored interval of Ben Nevis L-55 range from 9.2 to 22.7%, with an average value of 15.9% (Table 1) (Core Laboratories Canada Ltd., 1999). Visual porosity estimates of the five samples using the SimplePCI software on a blue-epoxy-impregnated thin section range from 4.9 to 27.2%, with an average value of 18.5% (Table 1). Microporosity is not measured in the five samples and is recorded as minor in the core-plug analysis report (Core Laboratories Canada Ltd., 1999). Core-plug porosity data of given facies

are thus in general agreement with porosity trends revealed in thin section and measurements.

Permeability values obtained for Ben Nevis L-55 core interval facies (LF1 and LF4) from the core-plug data range from less than 1 to 376 md and have an average value of 44.9 md (Table 1) (Core Laboratories Canada Ltd., 1999). Permeability data of the five samples using the probe permeameter range from 1.5 to 394 md and have an average value of 32 md (Table 1). Spot-permeability data of bioturbated core-slab samples reveal that the mud-rich *Ophiomorpha* burrows can locally reduce permeability by as much as approximately 33% through incorporation and concentration of silt-clay-grade material in burrow fill and lining (see Figures 4, 5). Conversely, sand-filled burrows such as *Thalassinoides* can enhance permeability by as much as 600% through removal of silt-clay-grade material from pore spaces (Figure 4). Although probe permeameter values correlate well with the corresponding core-plug data, the collection of probe data at 1-cm (0.3-in.) intervals enables a more comprehensive understanding of the heterogeneous nature of the Ben Nevis L-55 core interval.

## POROSITY AND PERMEABILITY TRENDS ASSOCIATED WITH BIOTURBATION

Porosity and permeability in the Ben Nevis Formation of well L-55 are found to be controlled by a combination of sedimentary, biogenic, and diagenetic processes. Clay and silt-rich laminae and bioclastic beds are associated with porosity and permeability reduction (Table 1). Bioturbation can either enhance or reduce permeability, dependent on the burrow type and the behavior of the trace-making organism in the Ben Nevis L-55 core interval.

Based on our studies of bioturbation in the Ben Nevis Formation, we consider that the burrowing activity of animals can be grouped broadly into five categories with predictable effects on porosity and permeability.

1. Sediment mixers cause indiscriminate mixing of sediment grains, increasing the isotropy or



- uniformity of the sediment by unsorting any grain-size trends, and through mechanical destruction of laminae. Sediment mixers burrow in the sediment without sorting the sediment into distinct burrow linings or fills. Clearly, the negative effect of diminished small-scale sorting is more than compensated for by the elimination of fine-grained laminae that act as baffles. For example, burrow-mottled (Figure 4) and diffuse to massive textures (Figure 5) create intense to complete levels of bioturbation (>90%) with the net effect of permeability enhancement (e.g., diffuse laminae, 5.89–33.60 md and interlaminated sandstone, 7.99–12.59 md; Figure 5C).
2. Sediment cleaners increase isotropy of the sediment by selectively removing fine-grained material (e.g., pore-filling clay-silt and organic matter) from the sediment by ingestion and subsequent defecation of fines into the water column or creating a current within the near-burrow environment. Burrows consisting of well-sorted clean sandstone fill, relative to enclosing host sediment, are considered to be produced by sediment-cleaning organisms with the net effect of permeability enhancement (e.g., *Thalassinoides* burrow is 31.28 md, the adjacent *Ophiomorpha* burrow is 1.54–15.71 md, and the mean permeability for the sample is 18.33 md; Figure 4I). *Thalassinoides* traces with clean sandstone halos could be categorized as sediment cleaners (see Figures 2I–L, 4G–I).
  3. Sediment packers incorporate finer grade material (e.g., clay and fine organic matter) from the host sediment into burrow fills and/or linings decreasing isotropy of the sediment. Packing of the clay-silt-size fraction into pore space by organisms locally reduces permeabilities (e.g., *Ophiomorpha* burrow permeability is 1.54–15.71 md, relative to 5.38–66.86 md of the surrounding higher permeability sandstone; Figure 4I). Burrows of *Ophiomorpha*, *Chondrites*, *Phycosiphon*, *Asterosoma*, and *Teichichnus* can be categorized as sediment packers (see Figures 3E–H; 4–6).
  4. Combination of sediment cleaners and packers overall decreases the isotropy of the sediment. These organisms pack mud into a mud-filled core and clean adjacent sediment, creating a coarser grained halo. *Phycosiphon* burrows are an excellent example of this combined behavior (see Figure 6G).
  5. Pipe-work builders open semipermanent burrows in sediment to perforate preexisting physical sedimentary fabrics. Such burrows are horizontal galleries connected at depth by vertical pipes to the sediment-water interface. Upon burrow abandonment, the burrow generally remains open and is passively filled with the overlying sediment at the sediment-water interface.
    - a. If the pipe work is filled with sand-grade material, high-porosity biogenic macropore networks can result. If such burrows are of sufficiently high density, effective permeability at the bed scale can be greatly improved. Bioturbation-enhanced porosity and permeability have been documented in several settings associated with sandstone-filled burrows into mudstone horizons, including *Glossifungites* ichnofacies (Weber, 1982; Gingras et al., 1999). This study includes examples of enhanced permeability in association with *Thalassinoides* burrows from the sandstone reservoir of the Ben Nevis Formation (see Figures 6F, 4G–I).
    - b. If the pipe network is filled with mudstone, the effect is generally a decrease in net-to-gross sandstone ratio but without a serious deleterious effect on host sediment reservoir properties.

## CONCLUSIONS

The burrowing activity of marine organisms produces a variety of burrows, tracks and trails, reworking lithic clasts, mineral grains, and organic matter to modify primary physical sedimentary fabrics. The action of bioturbators can be classified as sediment mixing, sediment cleaning, sediment packing, and pipe-work building strategies. Bioturbation has the potential to either increase isotropy by unsorting physically sorted grains or decrease isotropy by sorting grains and through creation of open-burrow systems.

In this sandstone-dominated reservoir, *Ophiomorpha* burrows are the most conspicuous element

of the ichnofauna throughout the well and are characteristic of several net-pay intervals. Although our research demonstrates that the conspicuous *Ophiomorpha* burrows reduce porosity and permeability, the subtle sand-filled burrows of *Thalassinoides* burrows are recognized as enhancing petrophysical properties in the net-pay intervals.

*Ophiomorpha* burrows in the Ben Nevis Formation of well L-55 display sediment-packing behavior in which clay-silt-grade material is removed from the sediment and incorporated into burrow linings and fill, thereby markedly reducing porosity and permeability (e.g., 33%). *Thalassinoides*, the other key trace fossil classified as a sediment cleaner and pipe-work builder, increases isotropy and is related to enhanced porosity and permeability (up to 600% greater than the host sediment). Burrow mottling, diffuse laminae, and massive intervals unsort the primary sedimentary fabrics formed during deposition. In intensely bioturbated lithologies, bioturbation has the net effect of permeability enhancement.

The implication of animal-sediment interactions, for example, the porosity- and permeability-reducing sediment-packing activity within the *Ophiomorpha*-dominated ichnofabric, and porosity- and permeability-enhancing sediment-cleaning activity within the *Ophiomorpha-Chondrites-Phycosiphon* ichnofabrics, is easily identified in core and is hence of predictive value. Assignment of the aforementioned five categories of burrowing activity can be applied to other core analyses and can be used as a tool to predict effects on porosity and permeability.

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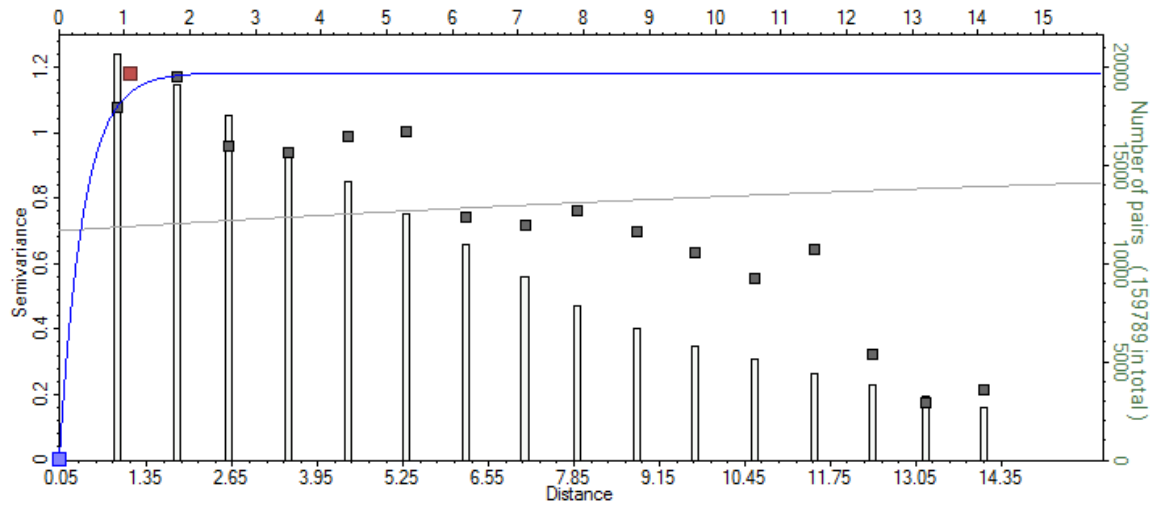
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## **Appendix C**

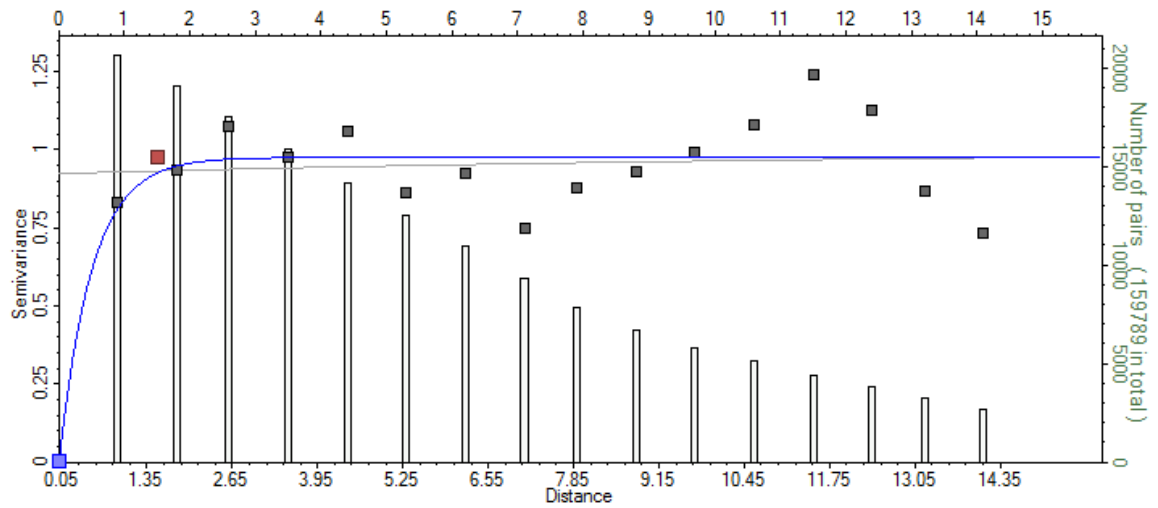
### **Vertical Facies Variograms for the Hebron Asset Reservoir Model**

## Zone 1

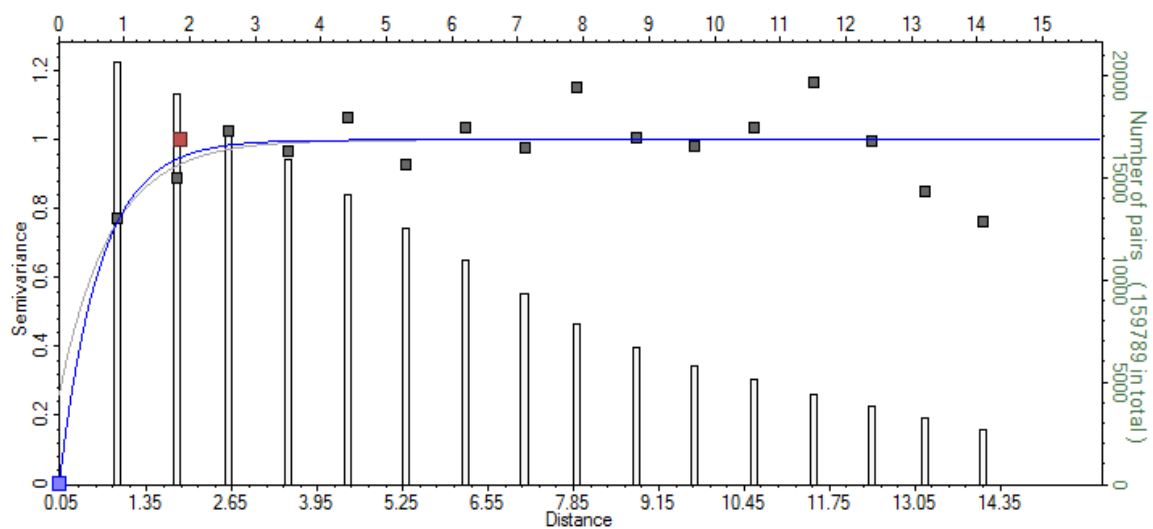
### Bioturbated Sand



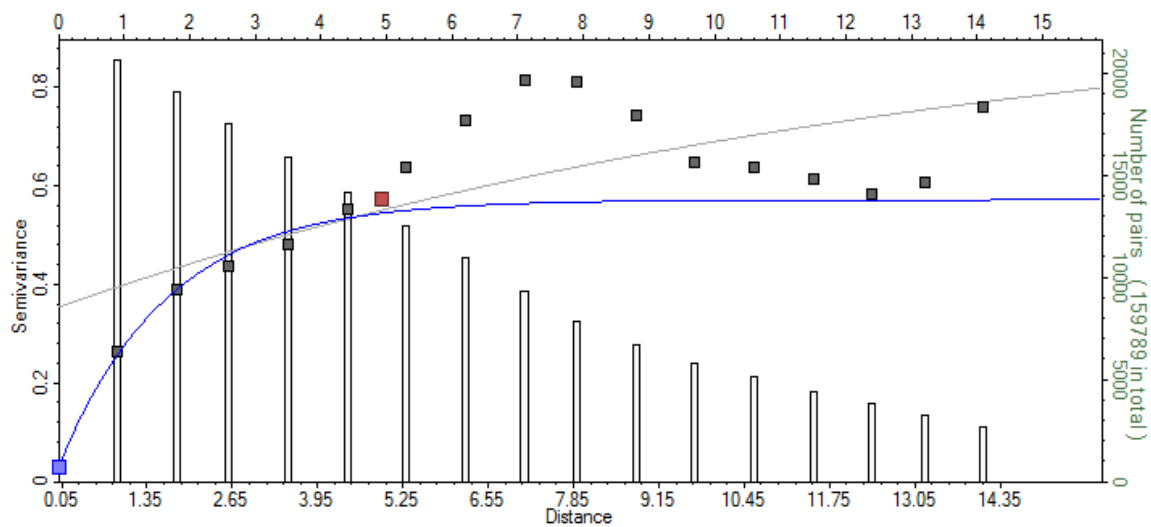
### Calcite



## Bioturbated Silt

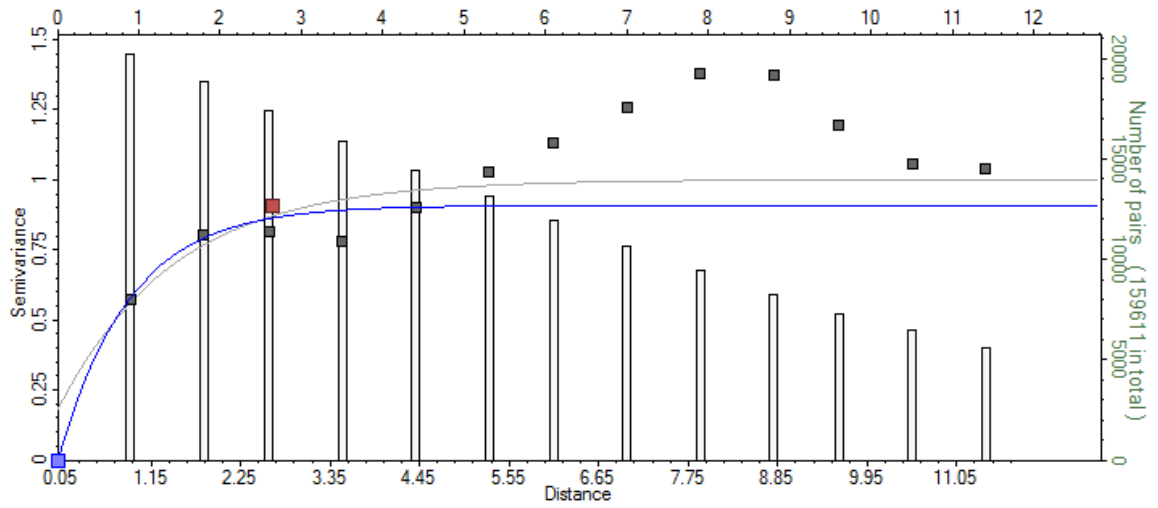


## Shale

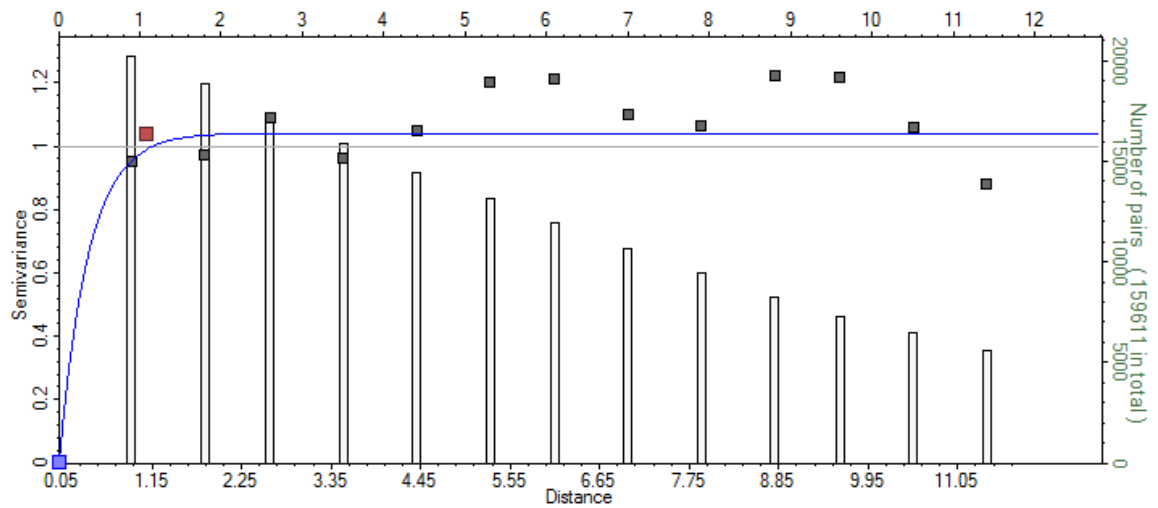


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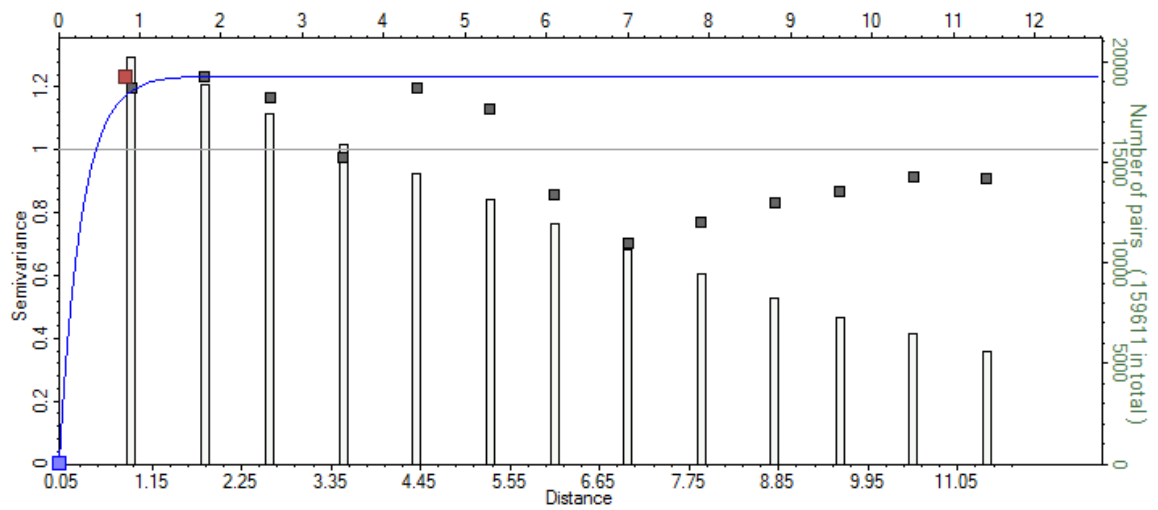
### Laminated Sand



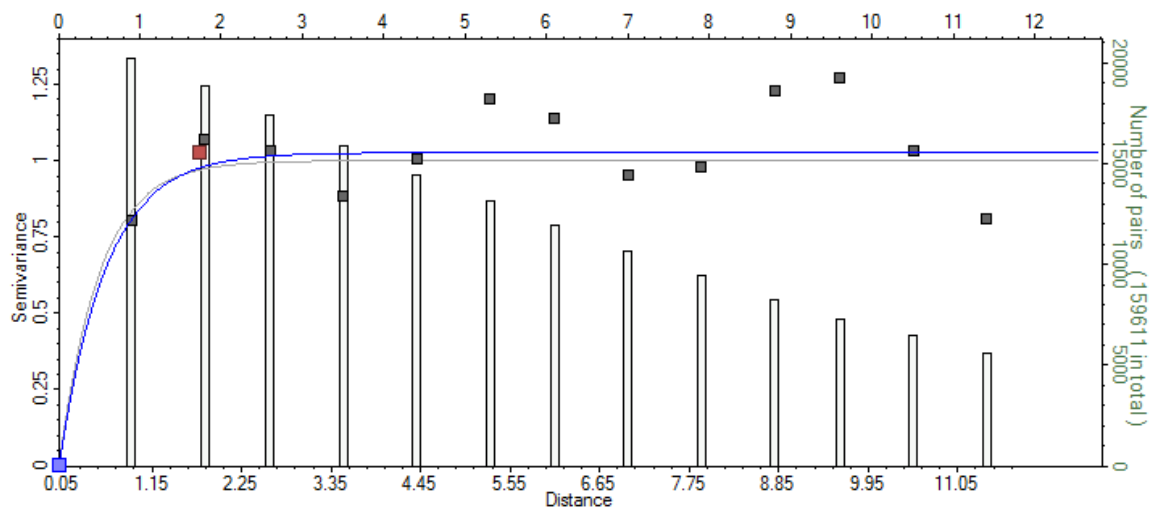
### Bioturbated Sand



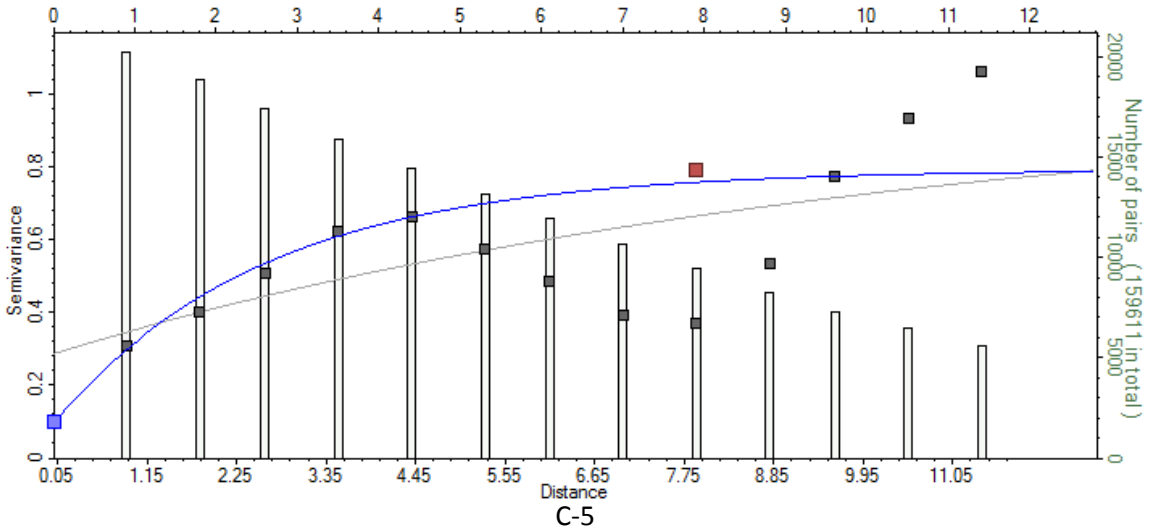
### Calcite



### Bioturbated Silt

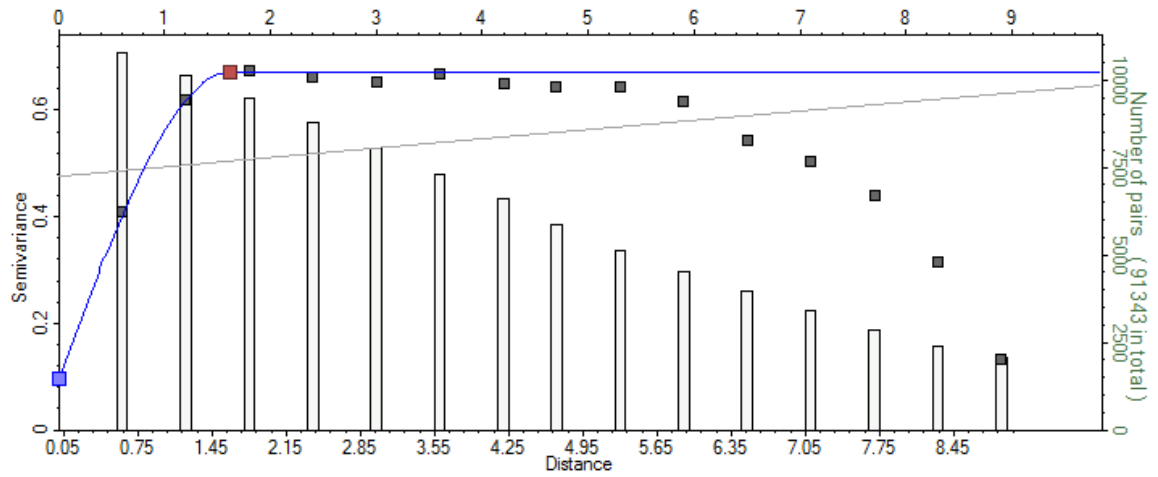


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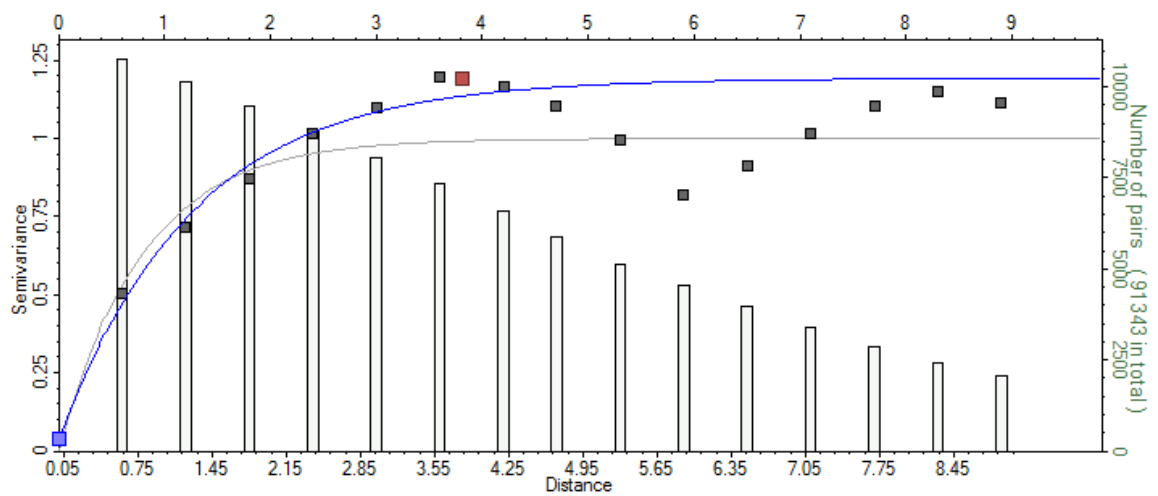


## Zone 3

### Laminated Sand

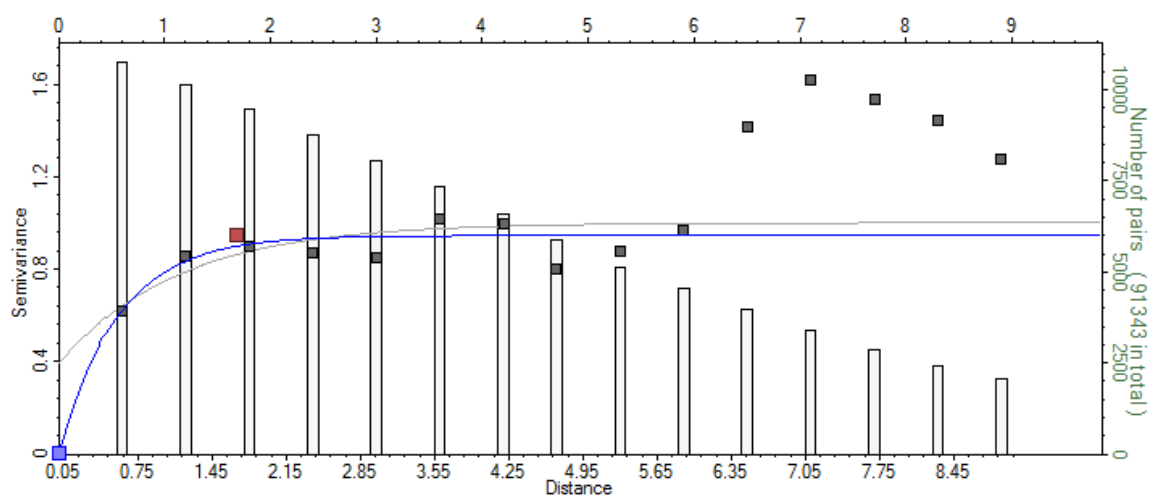


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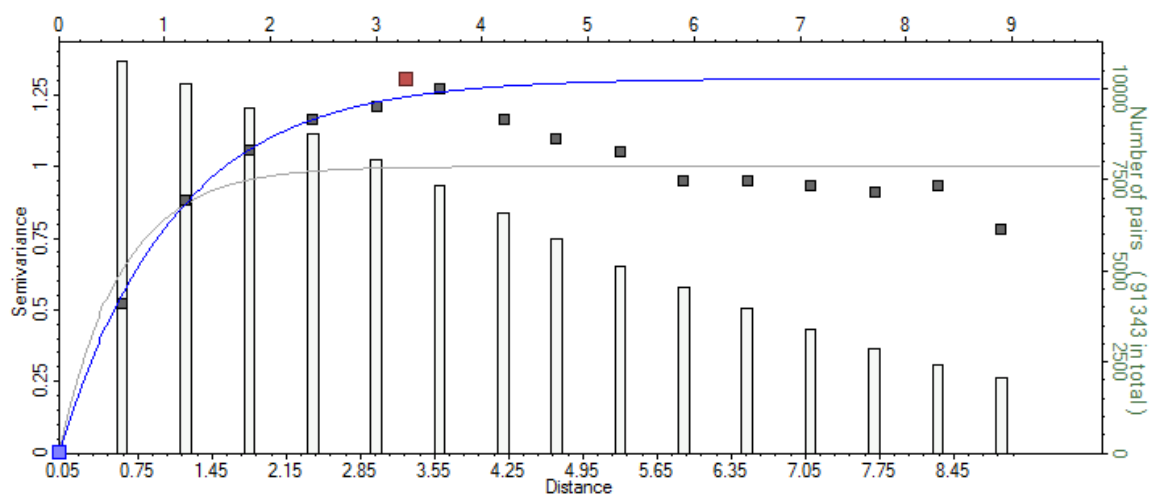




## Calcite

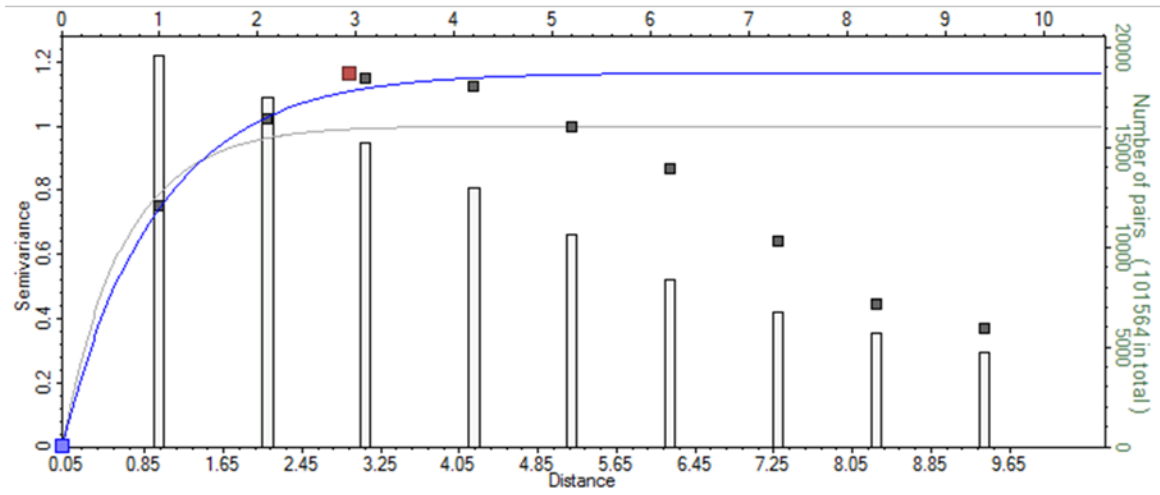


## Bioturbated Silt

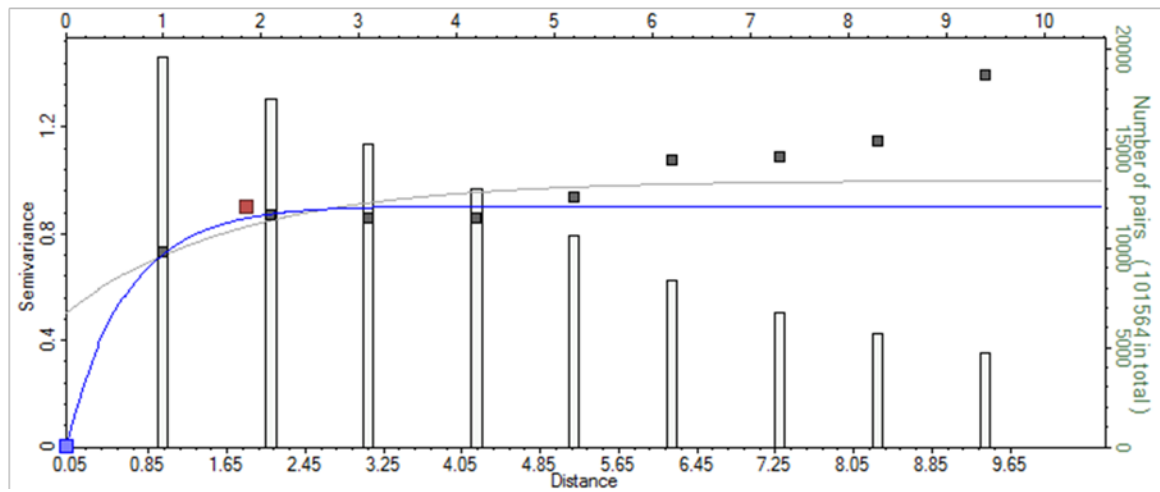


## Zone 4

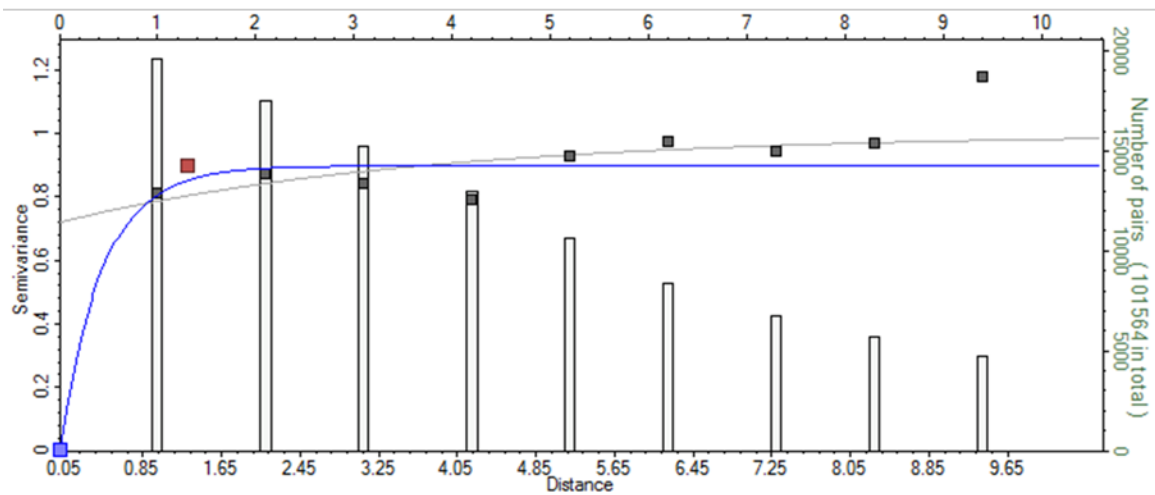
### Laminated Sand



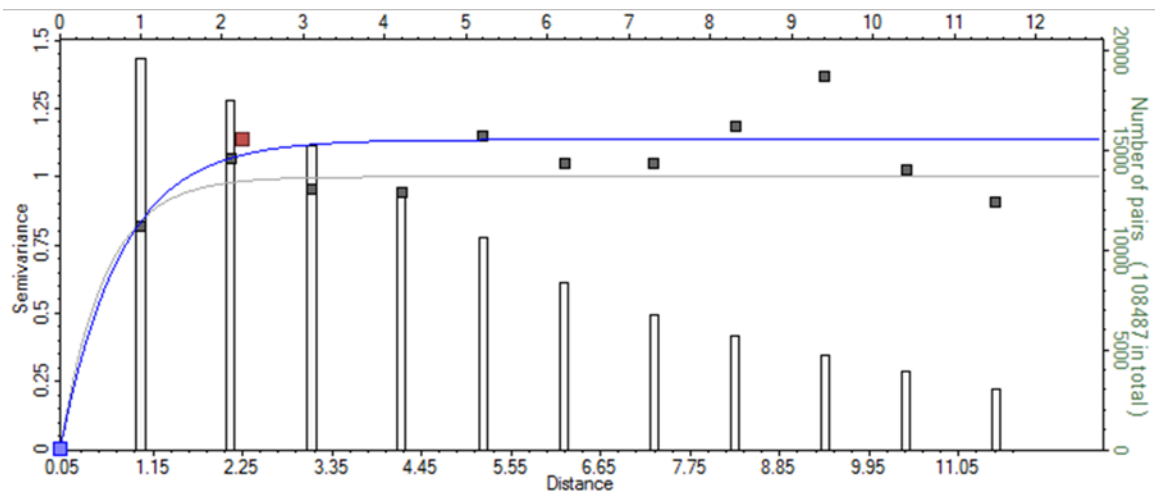
### Bioturbated Sand



## Calcite

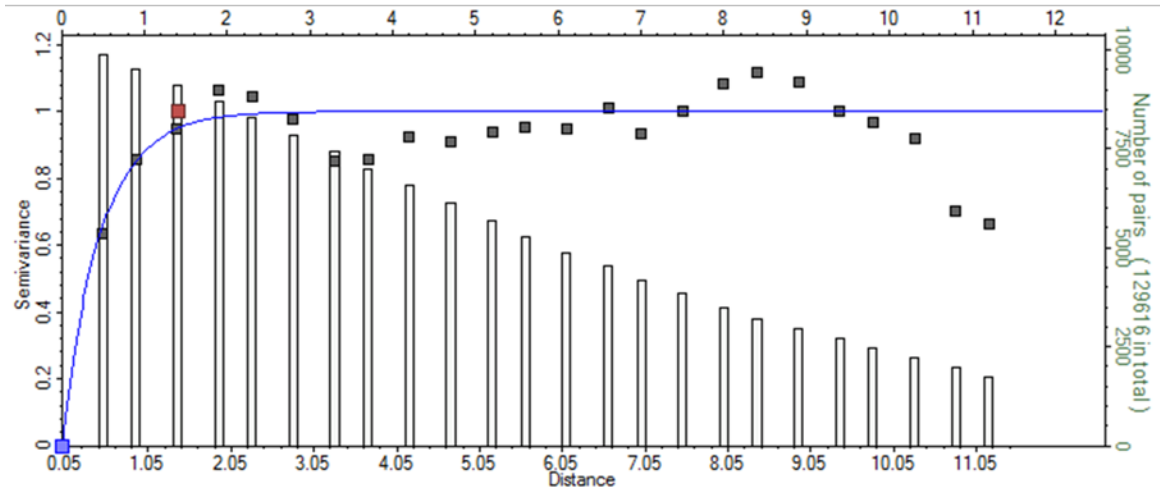


## Bioturbated Silt

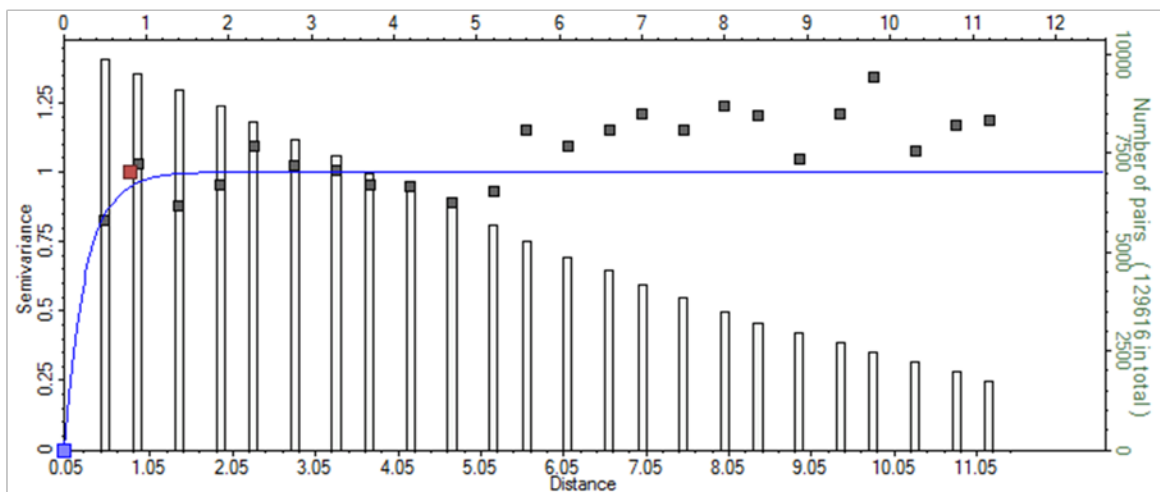


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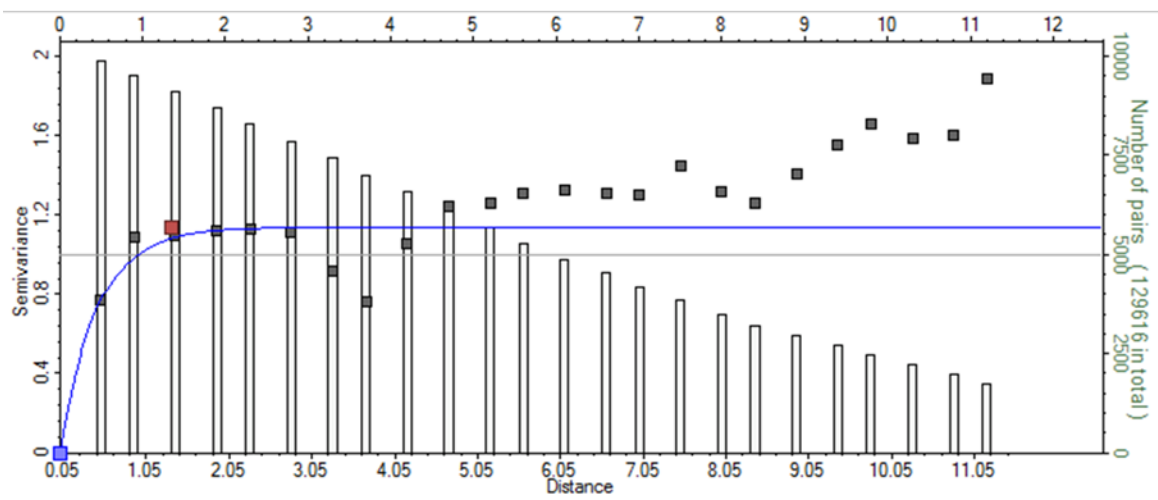
### Laminated Sand



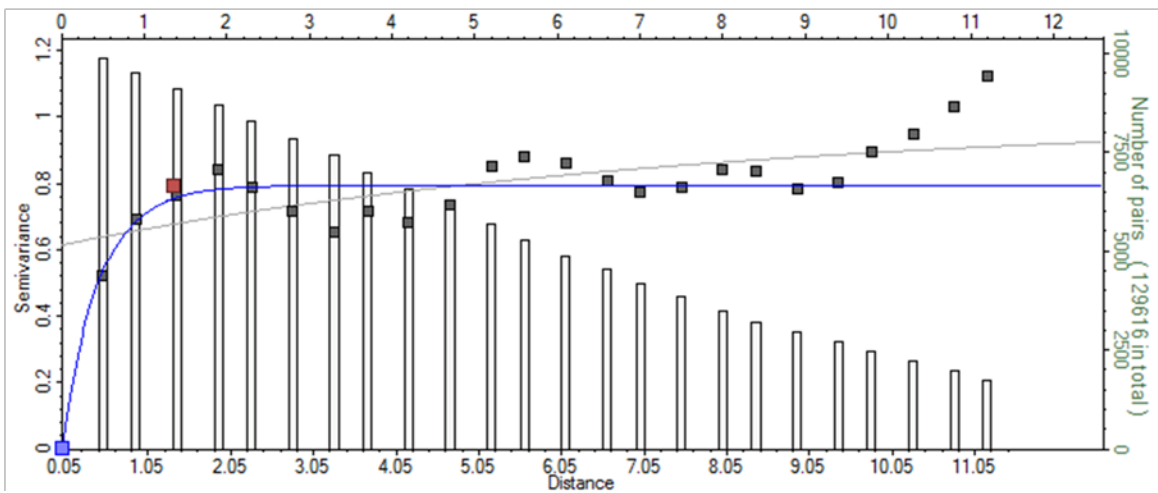
### Bioturbated Sand



## Calcite

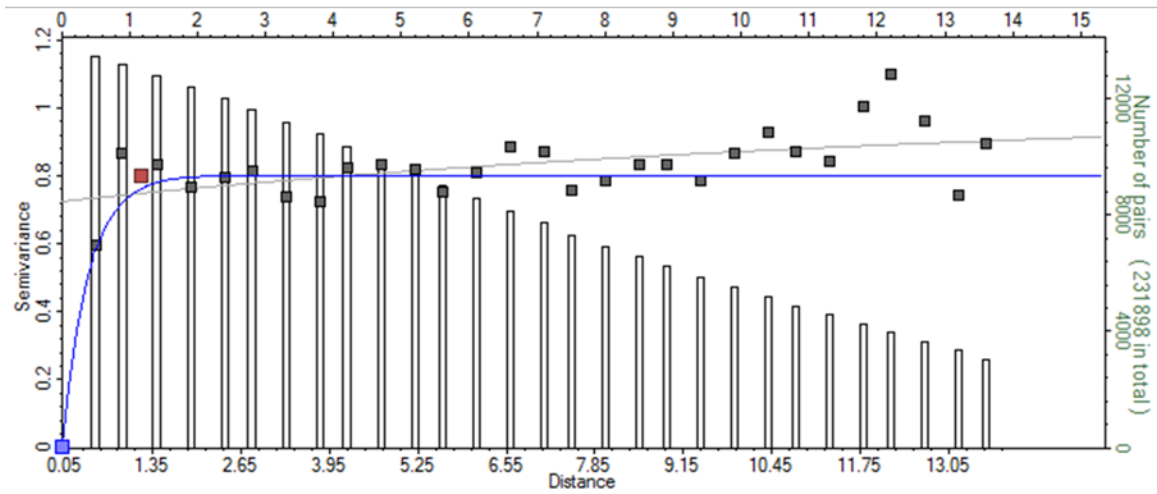


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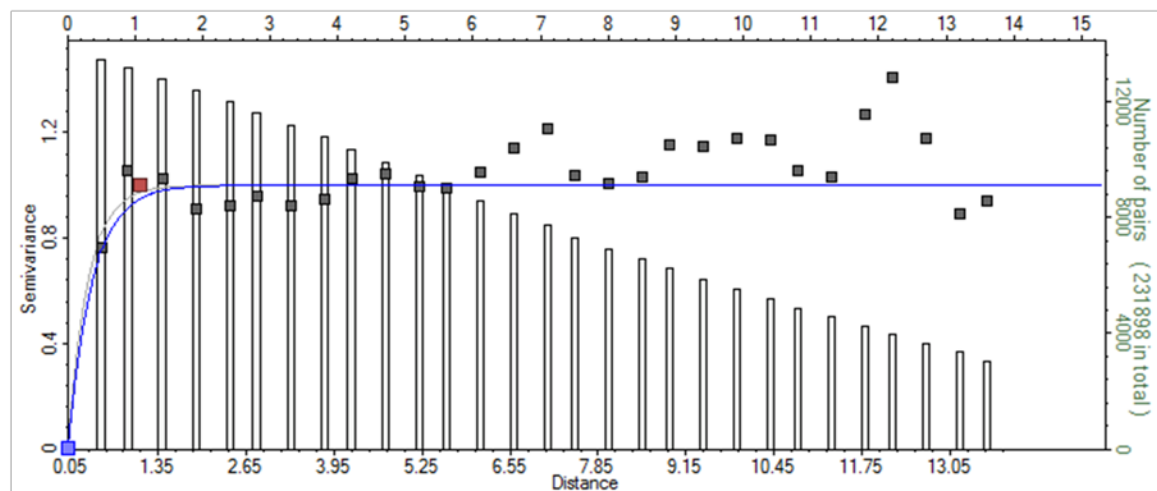


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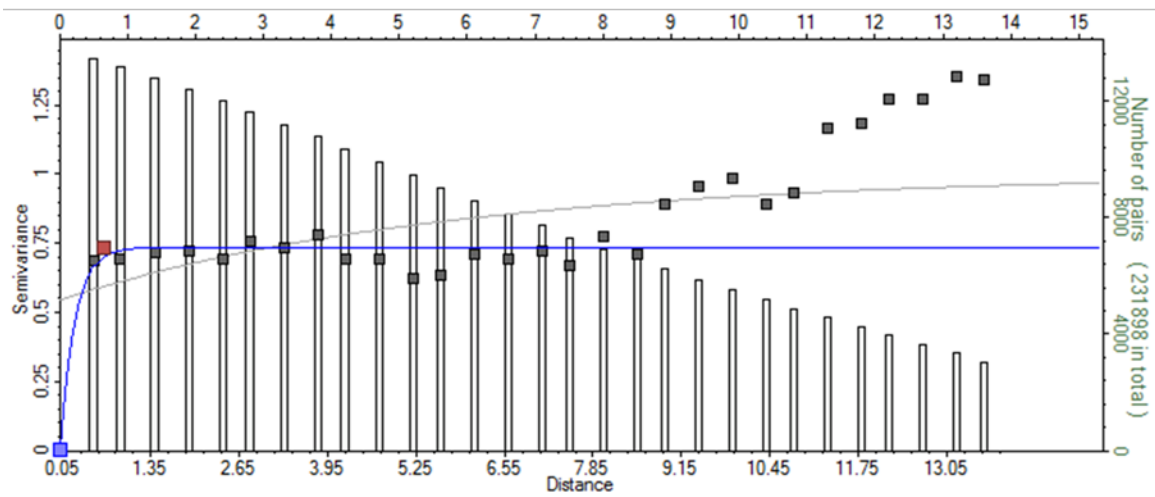
Laminated Sand



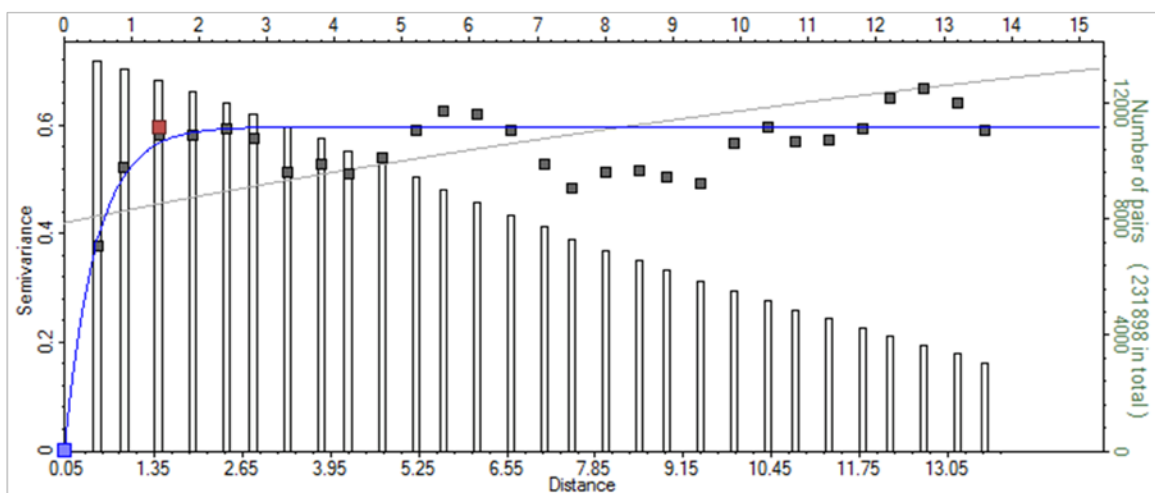
Bioturbated Sand



## Calcite



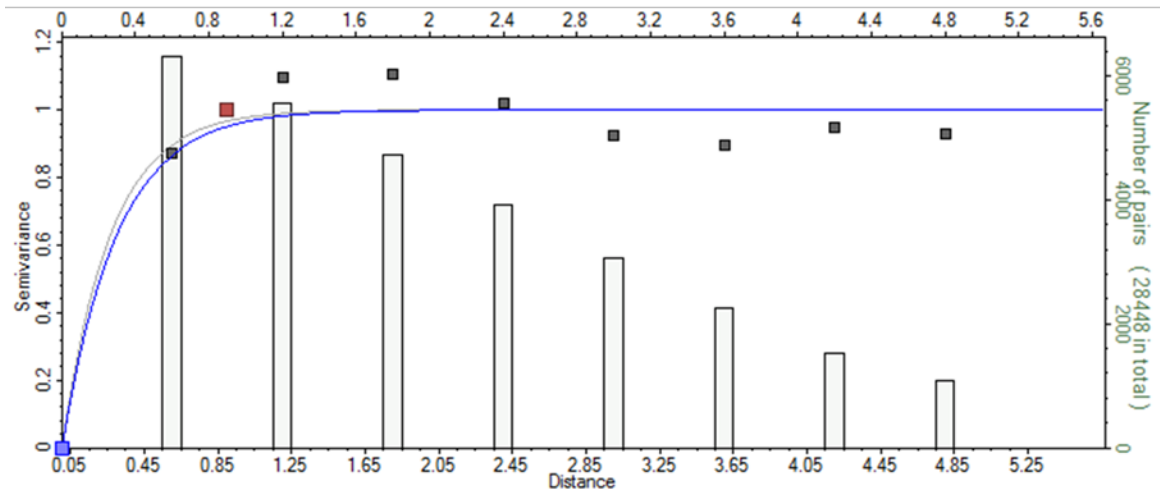
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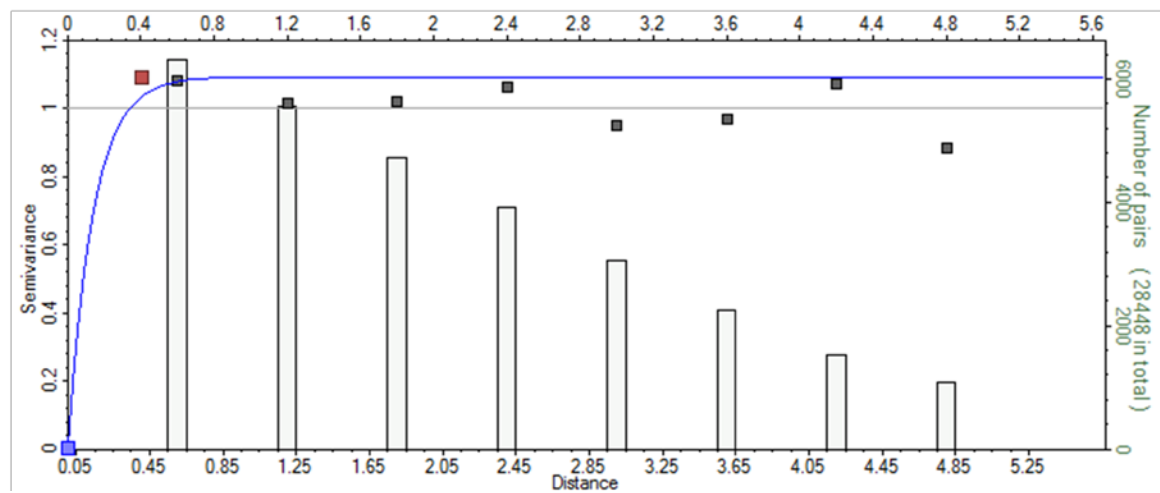


## Zone 7

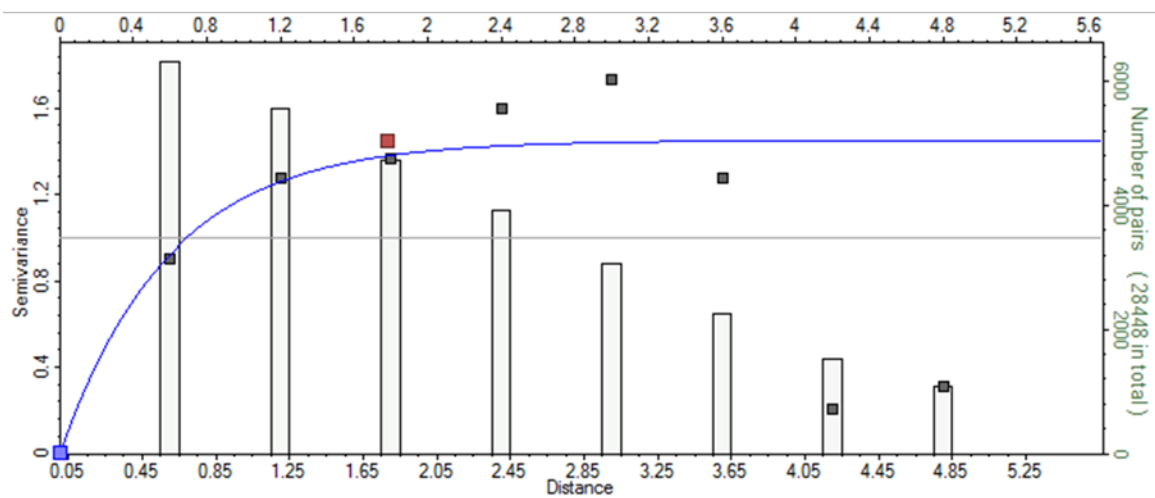
### Laminated Sand



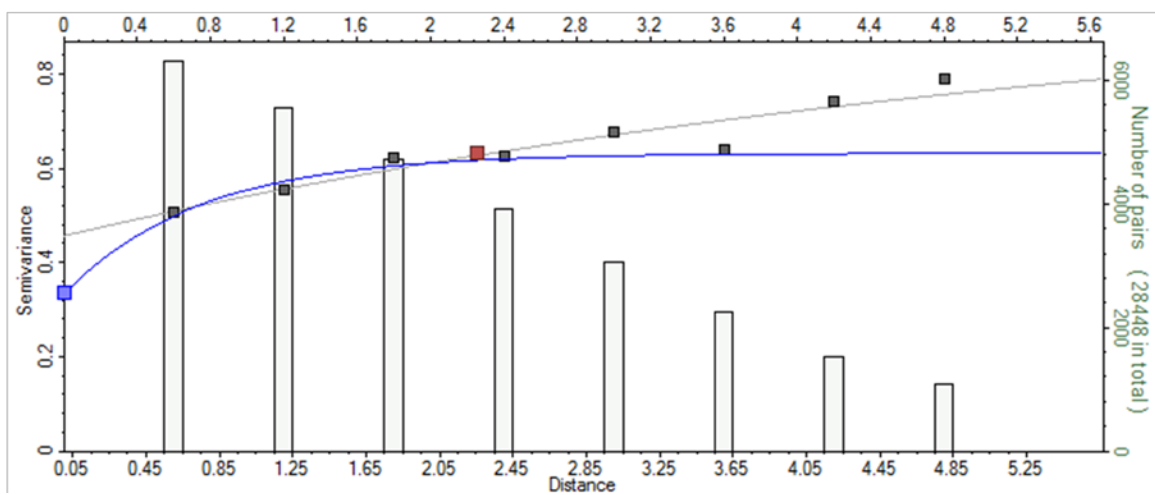
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## Calcite

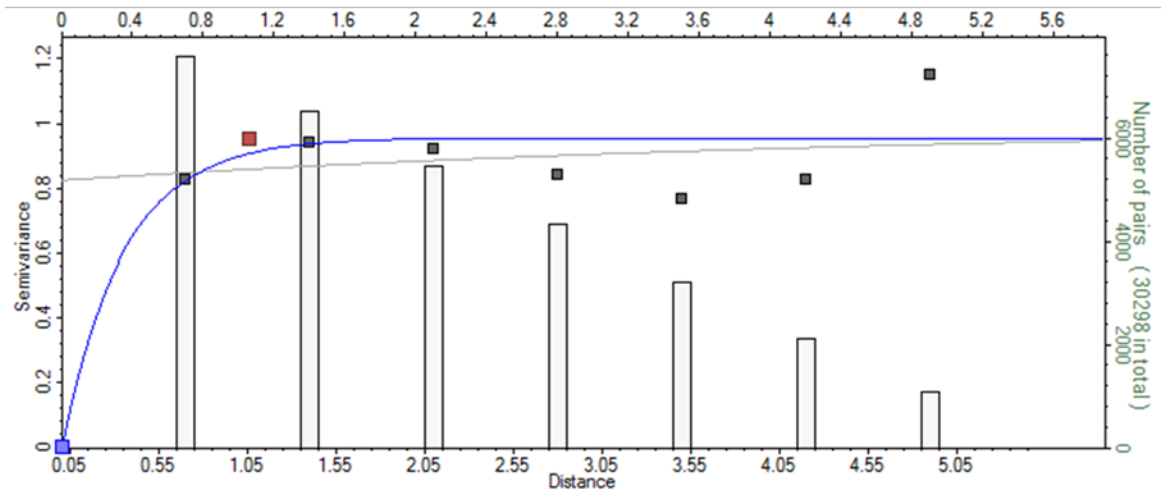


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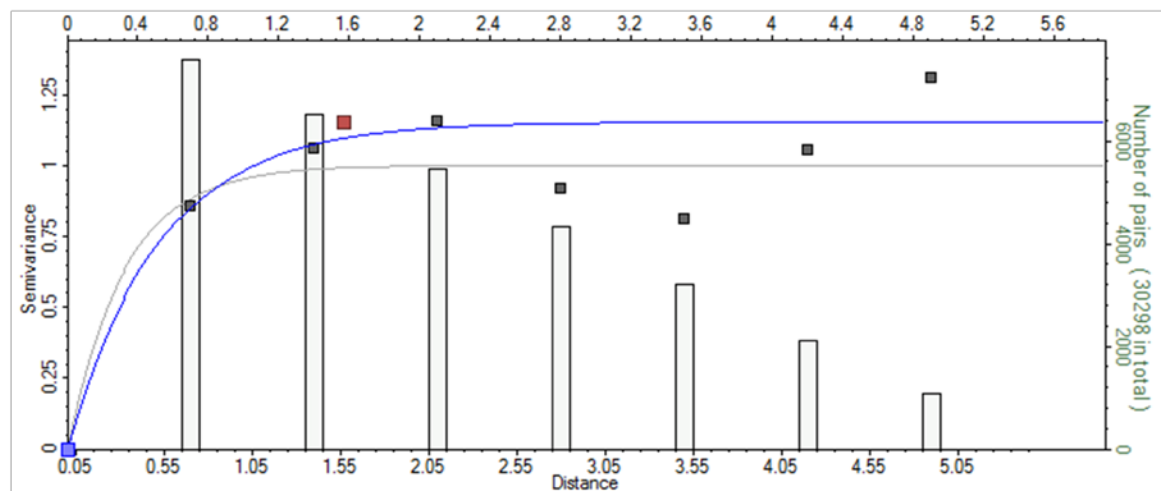


## Zone 8

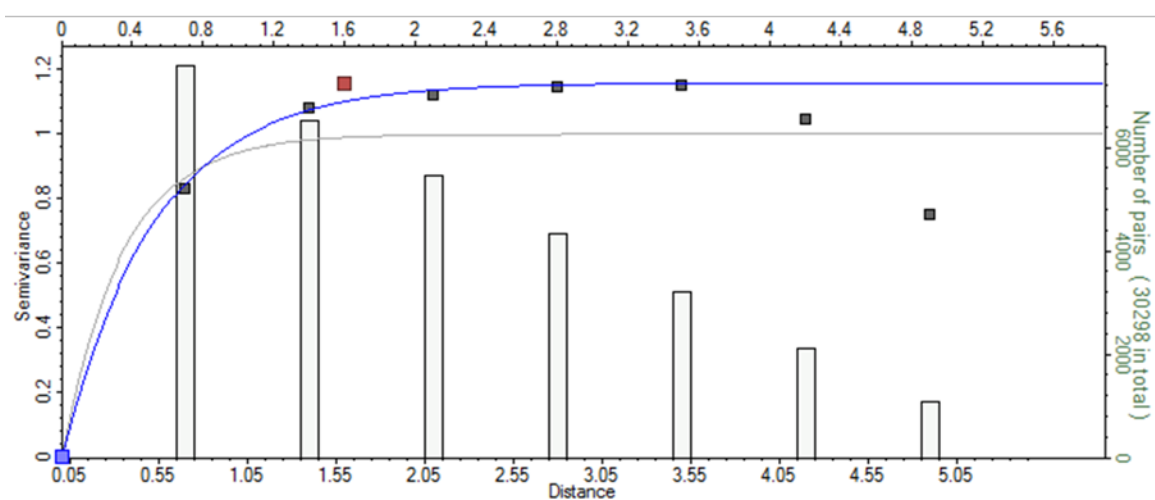
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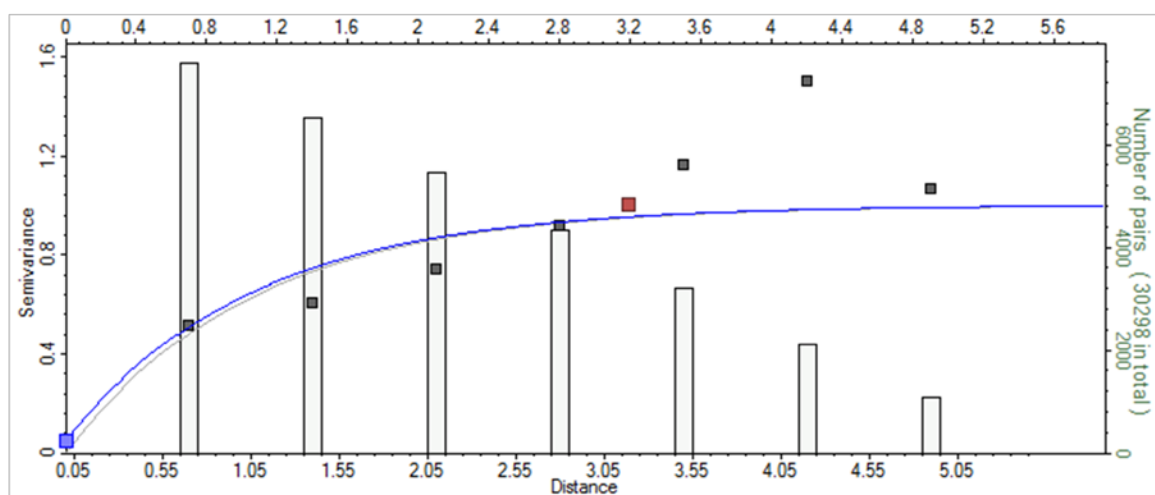
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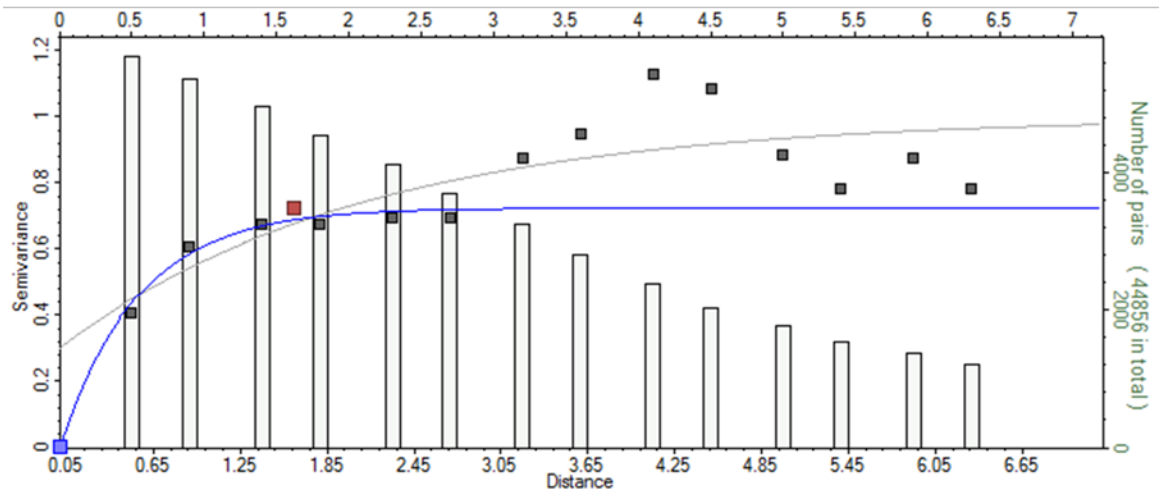


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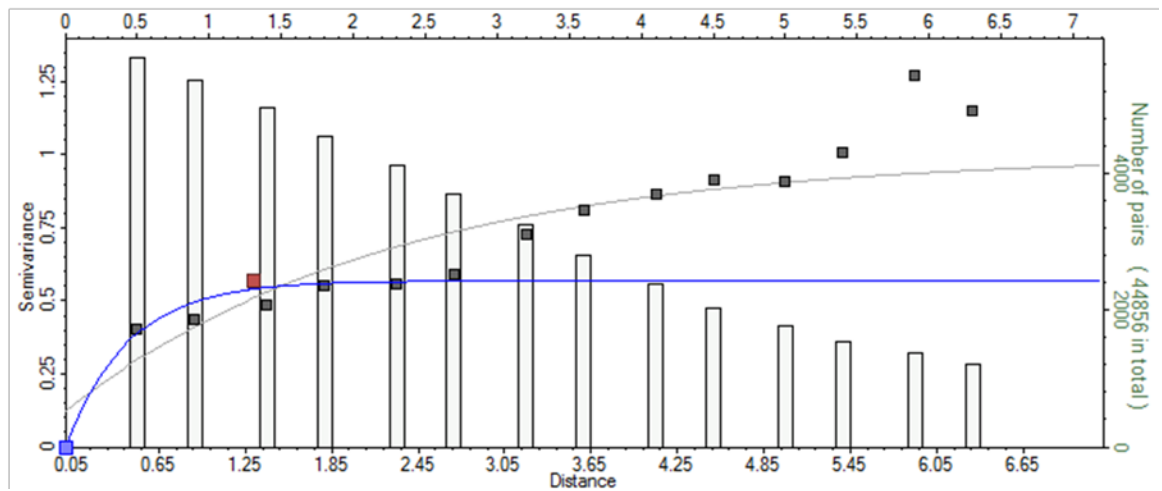


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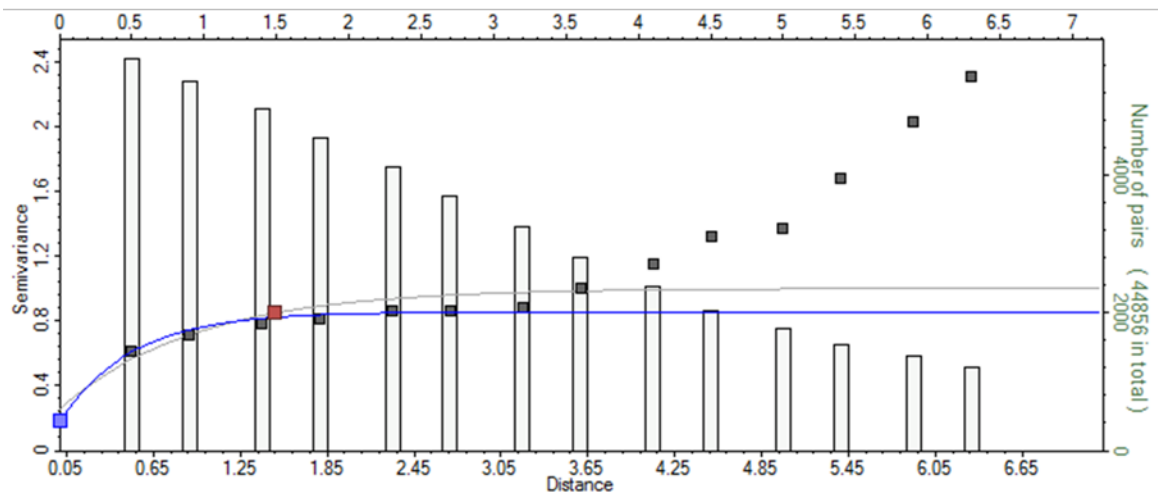
Laminated Sand



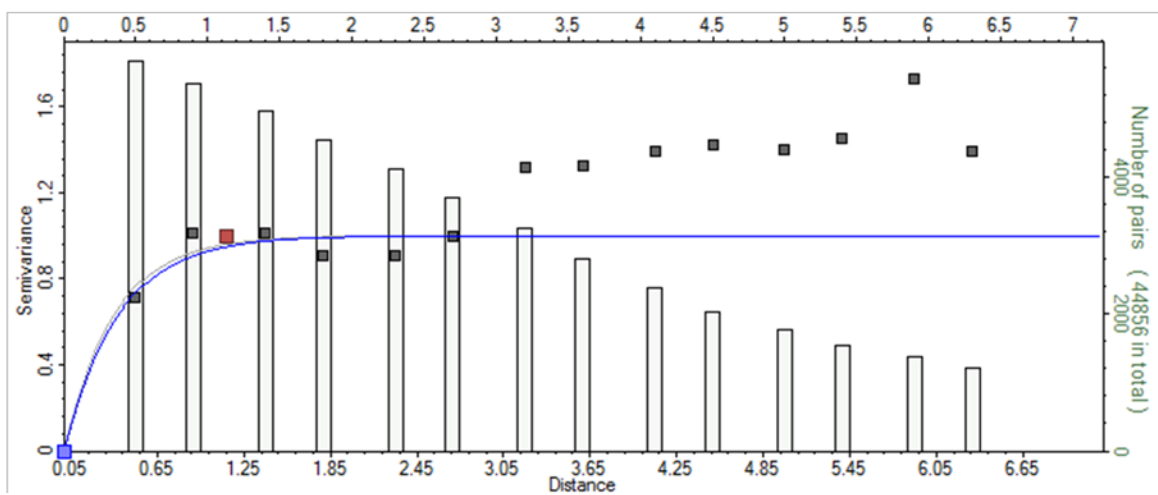
Bioturbated Sand



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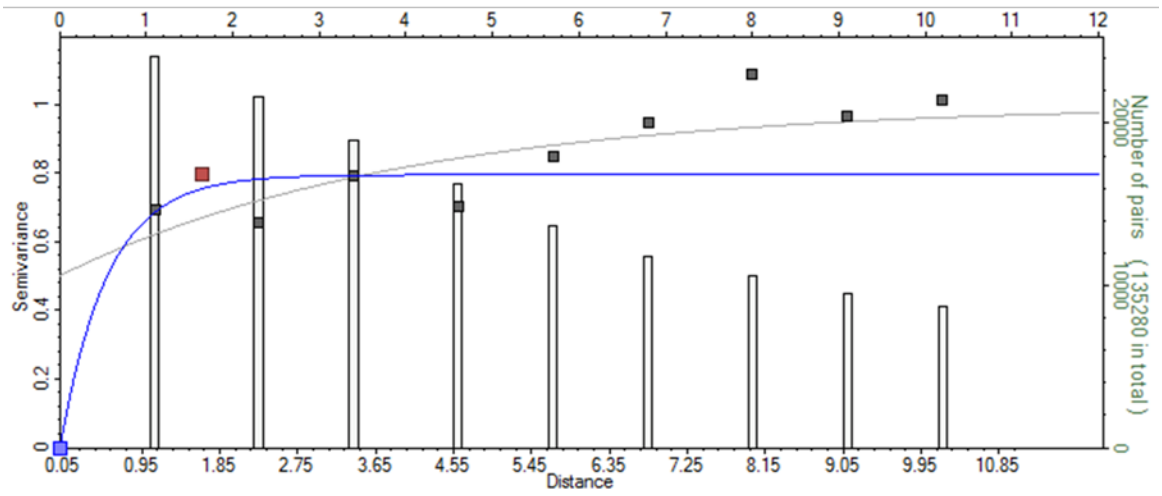


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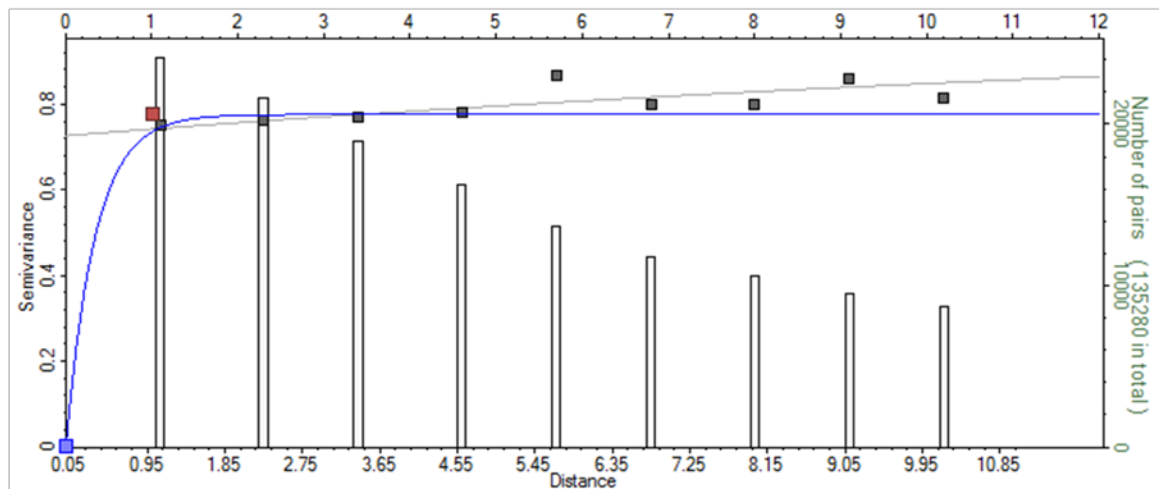


## Zone 10

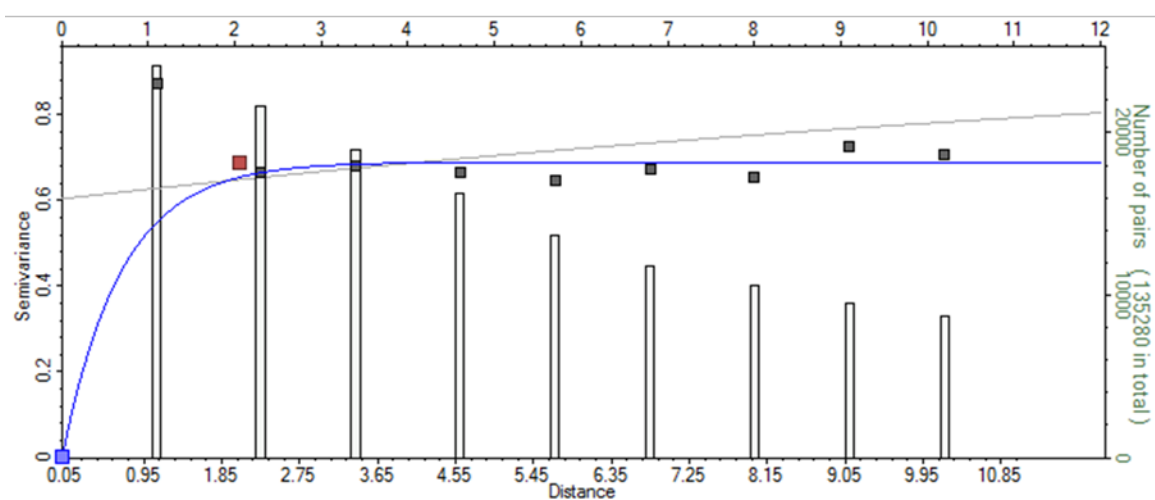
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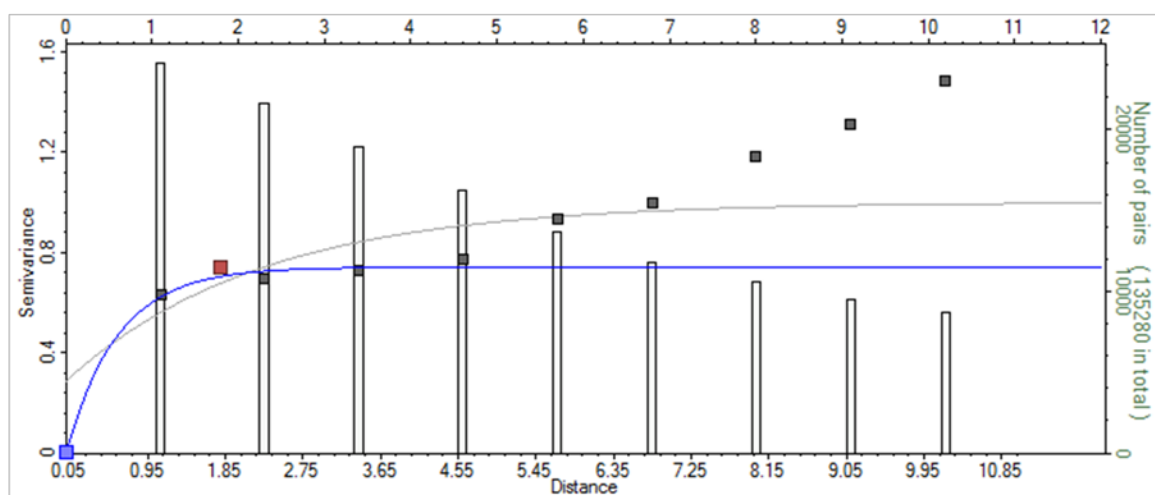
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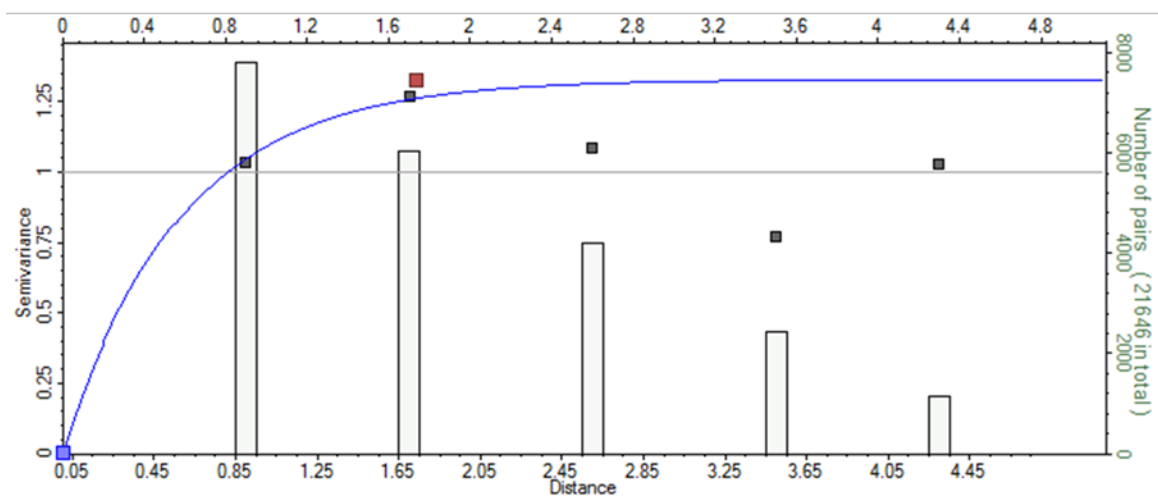
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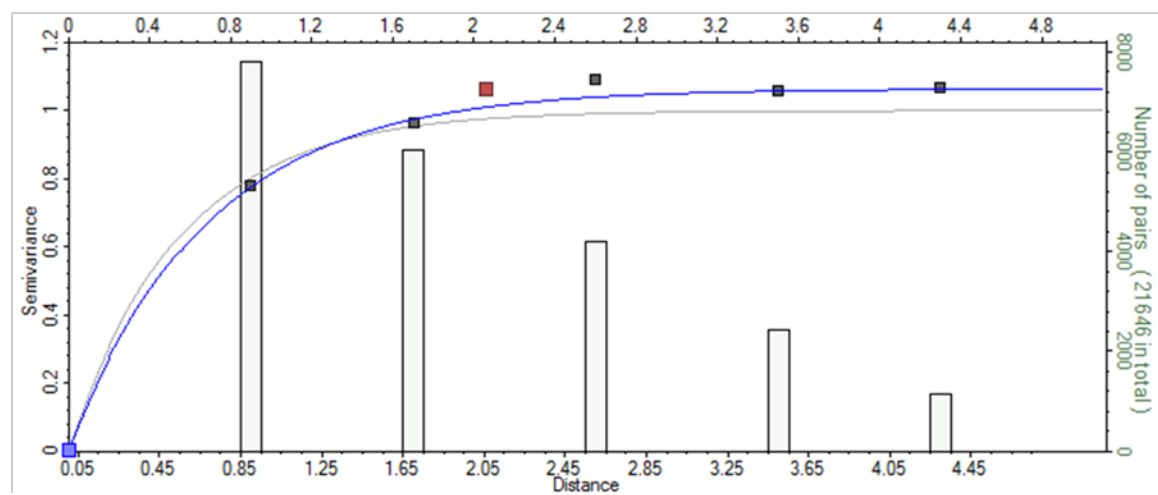


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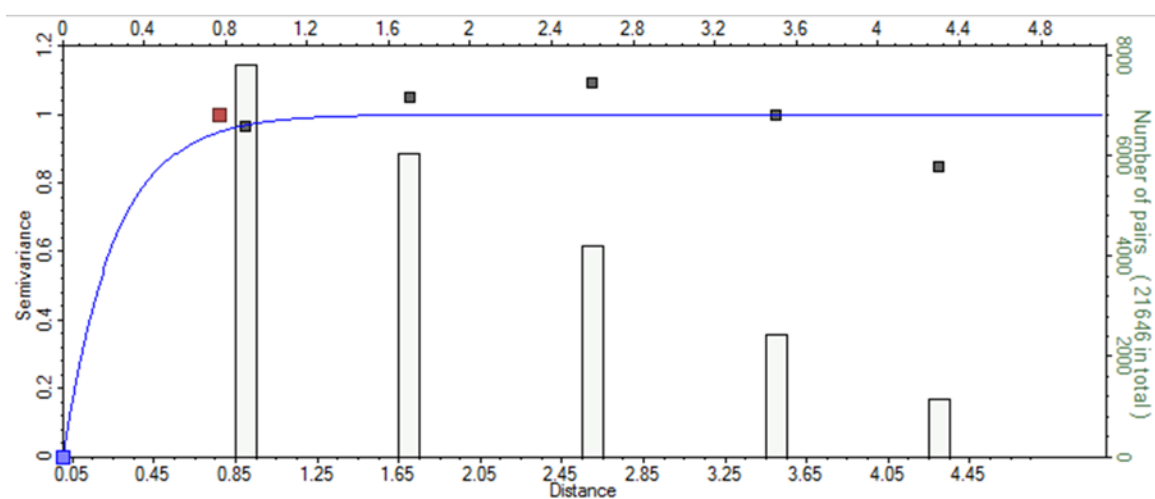
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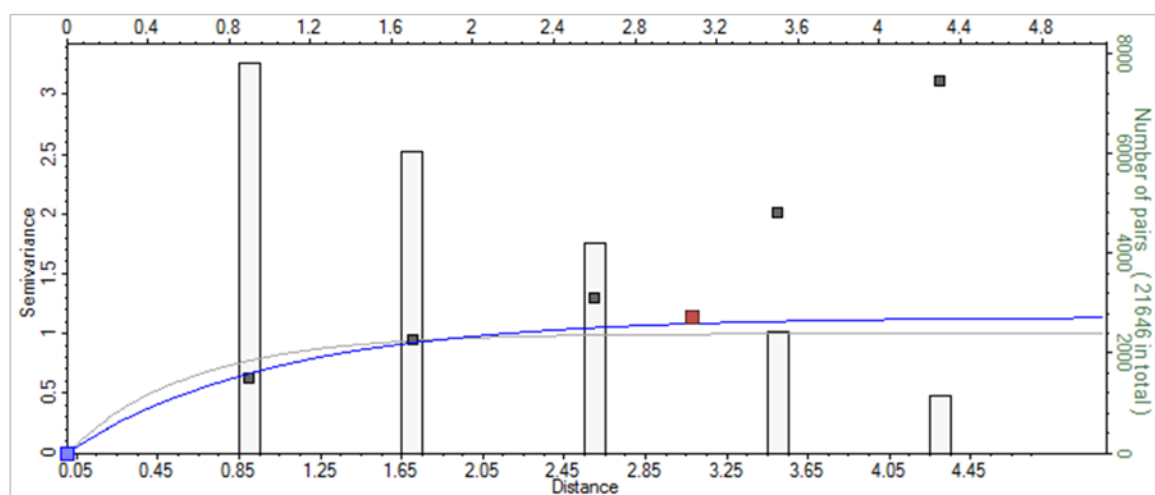
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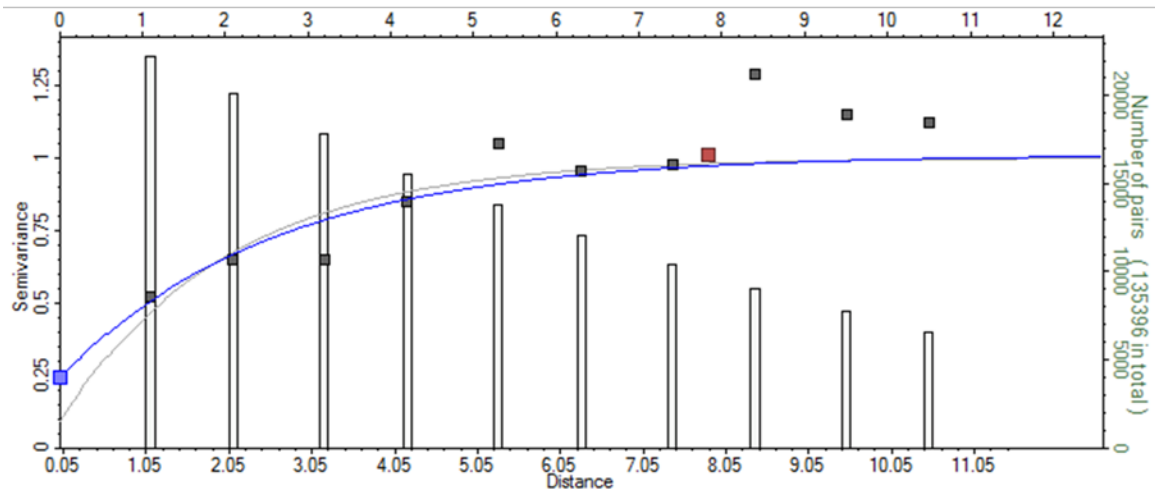


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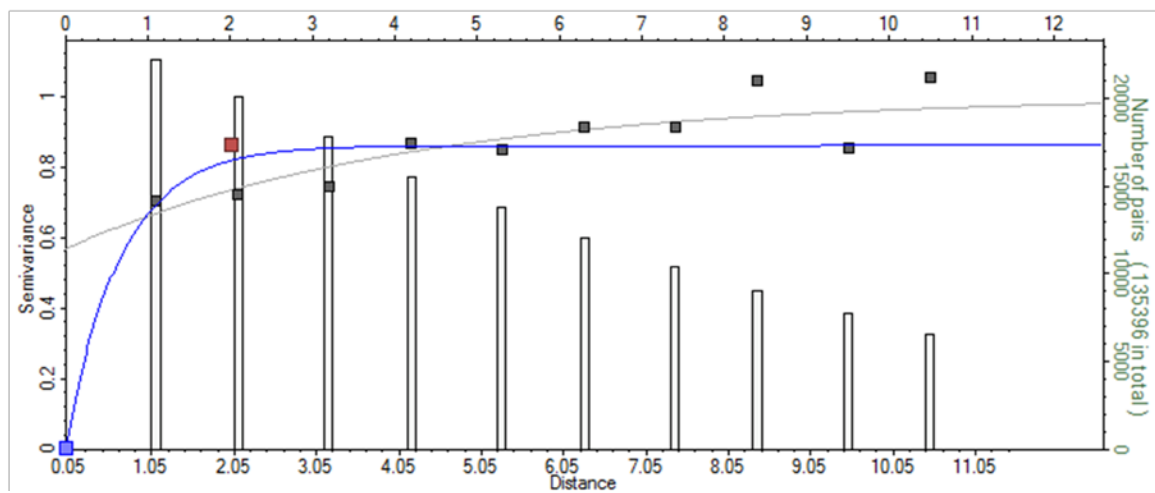


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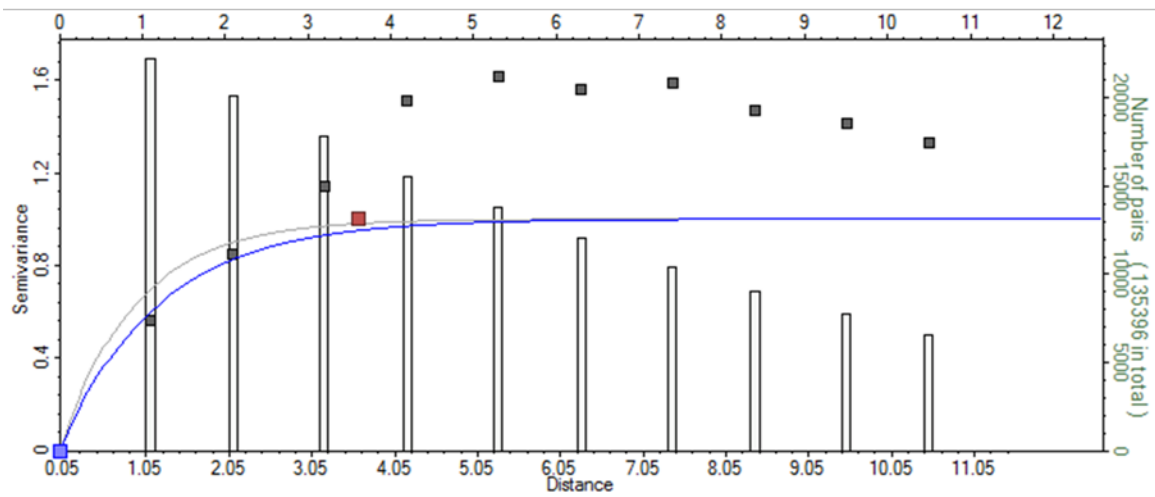
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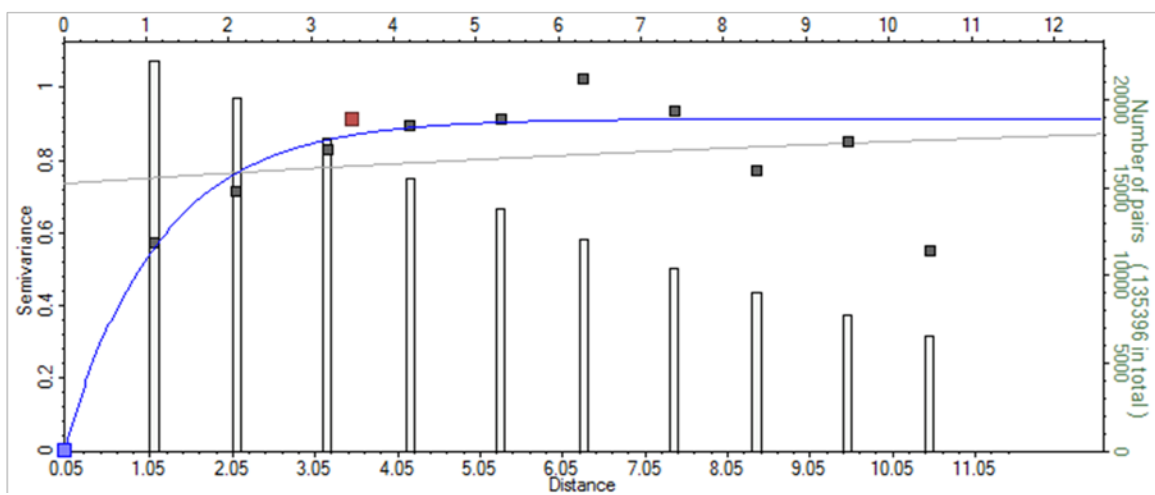
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## Calcite

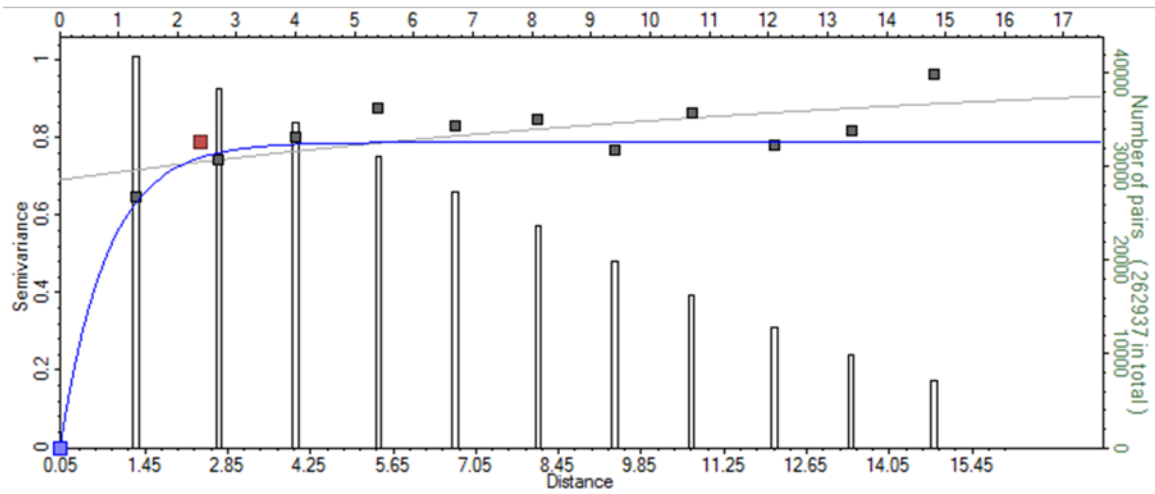


## Bioturbated Silt

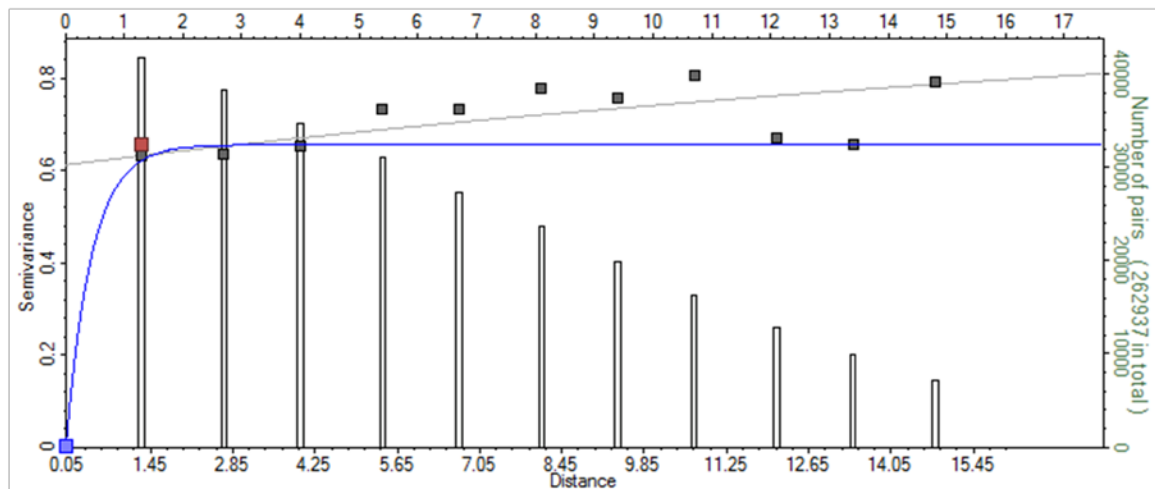


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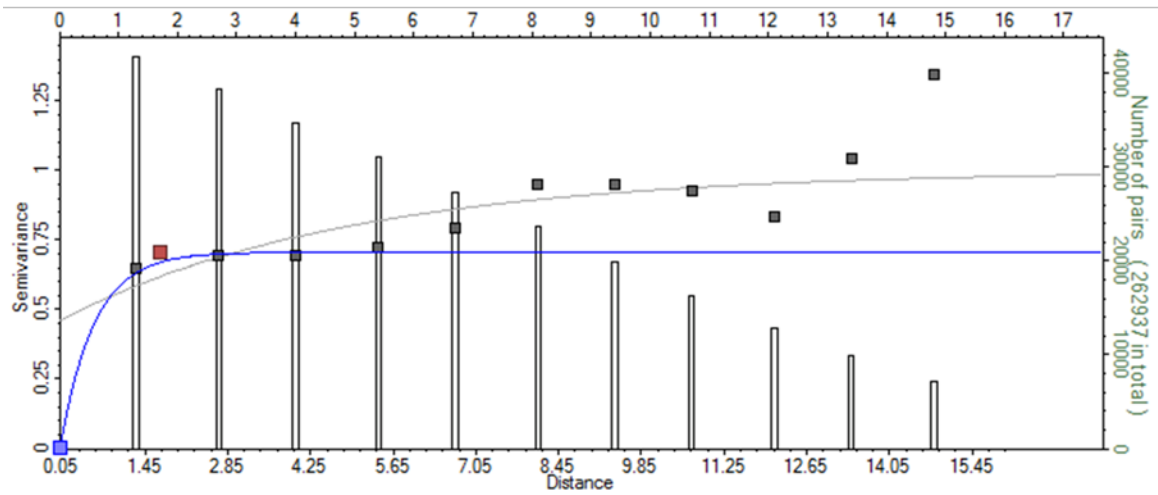
Laminated Sand



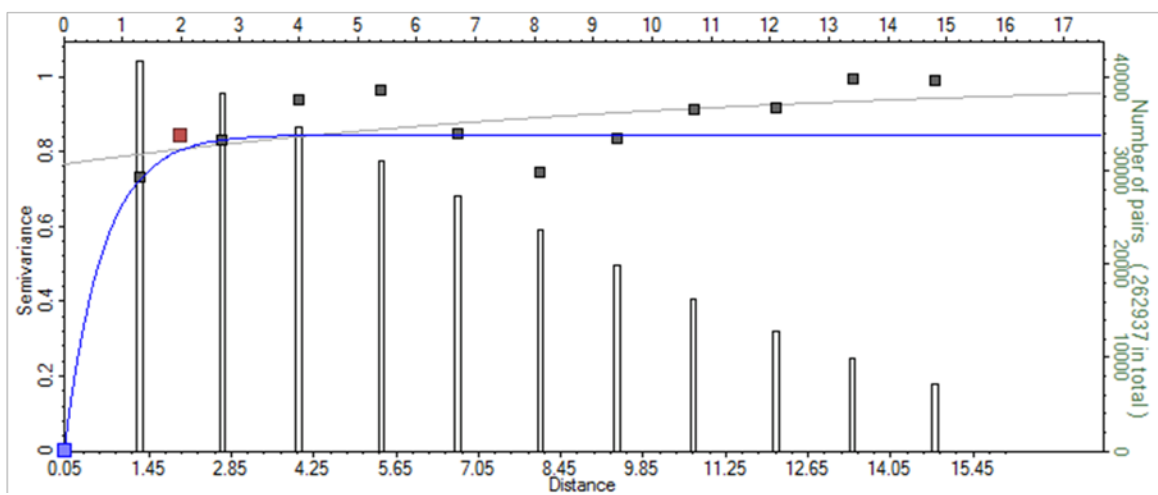
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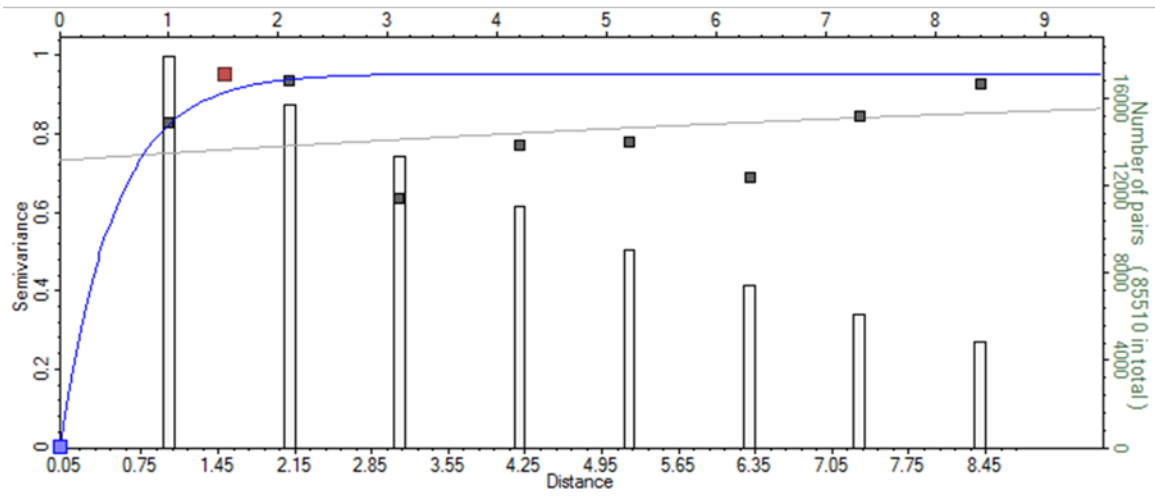


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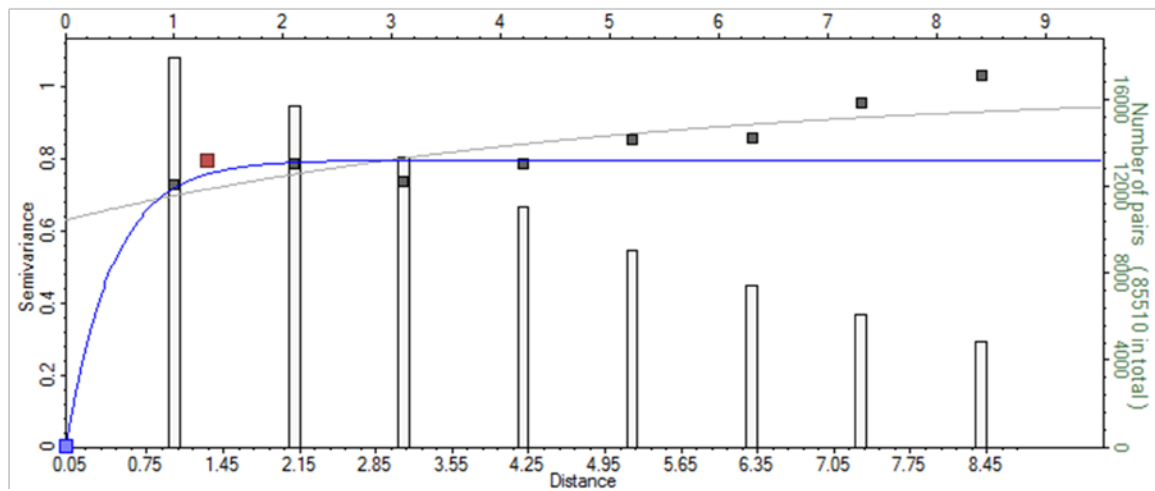


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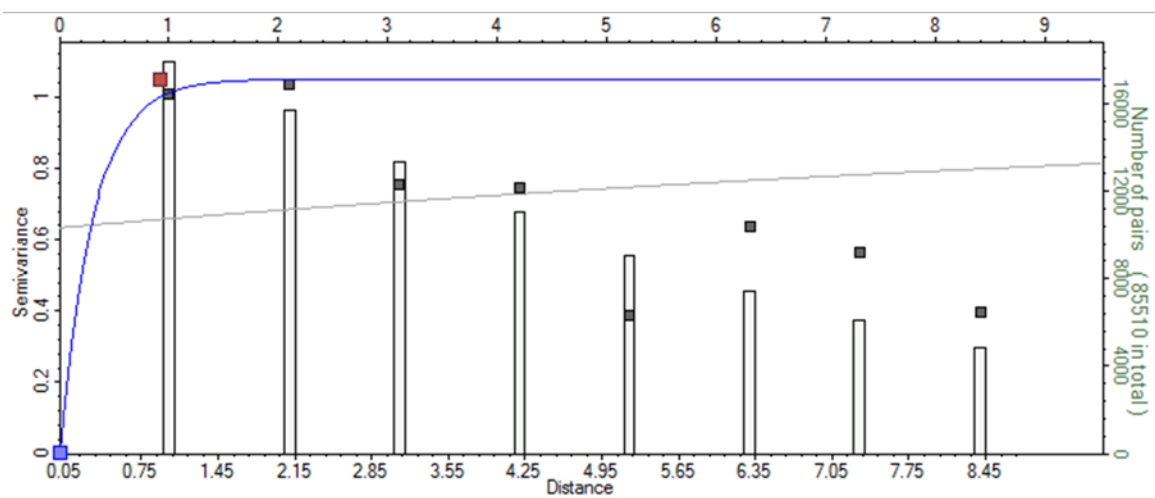
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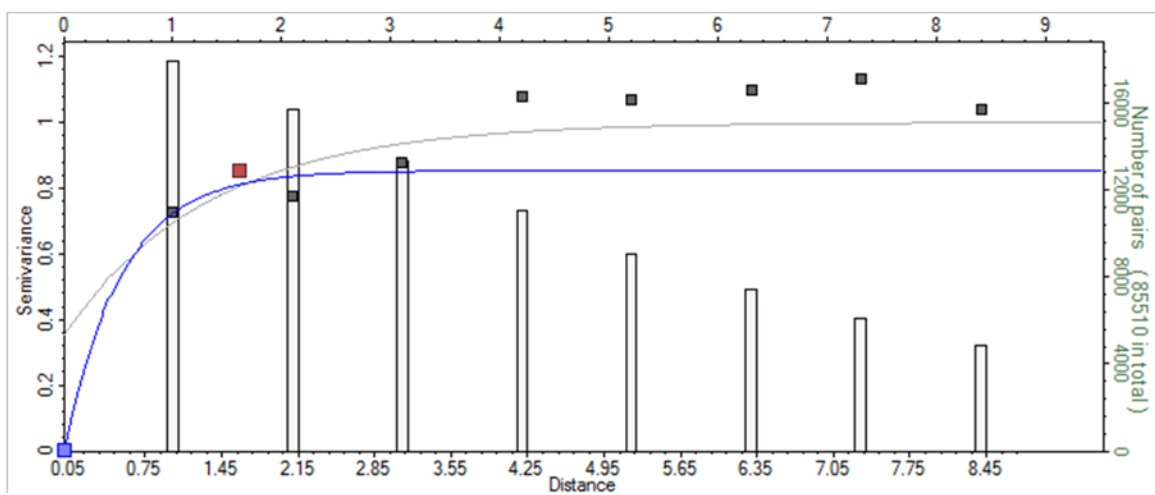
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## Calcite



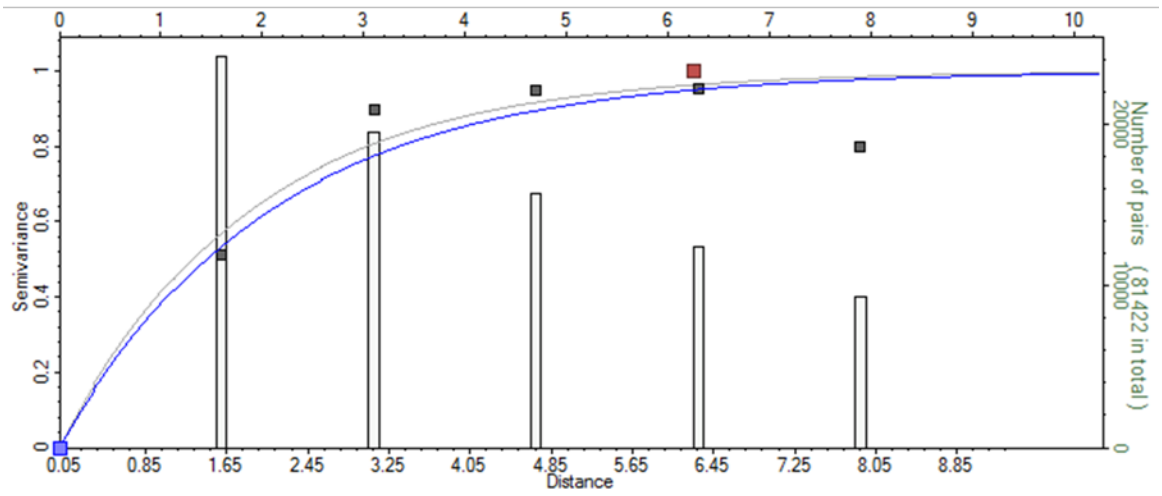
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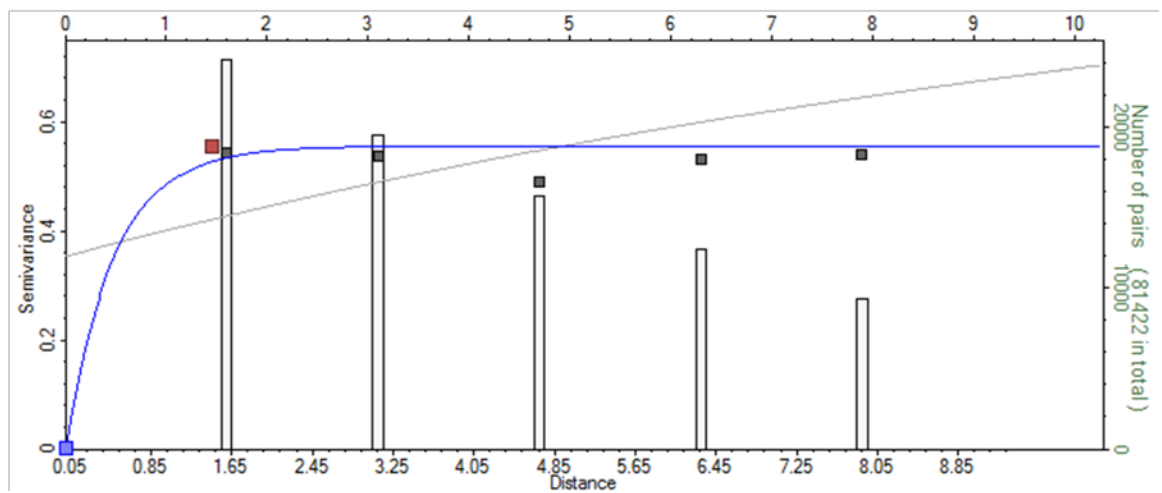


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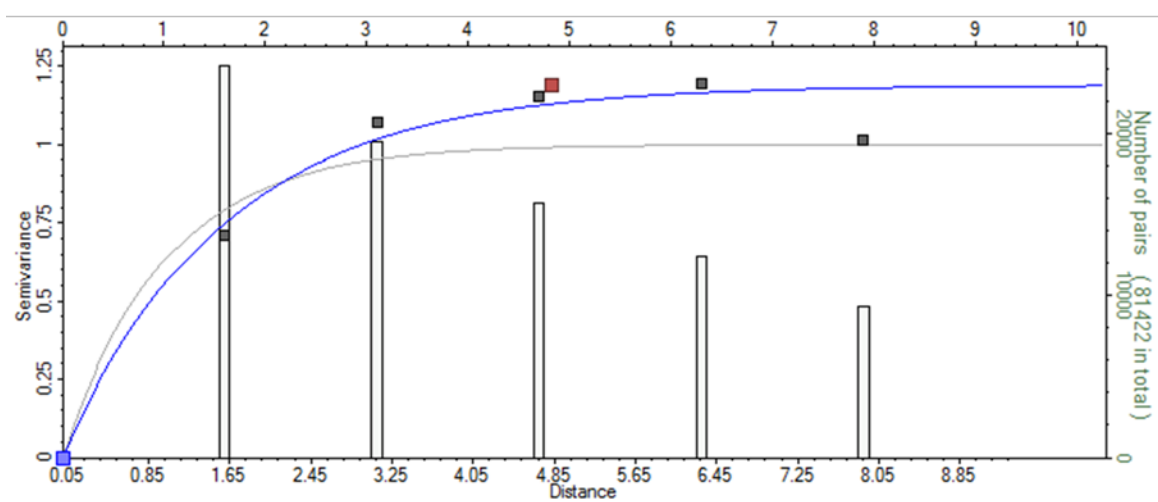
Laminated Sand



Bioturbated Sand

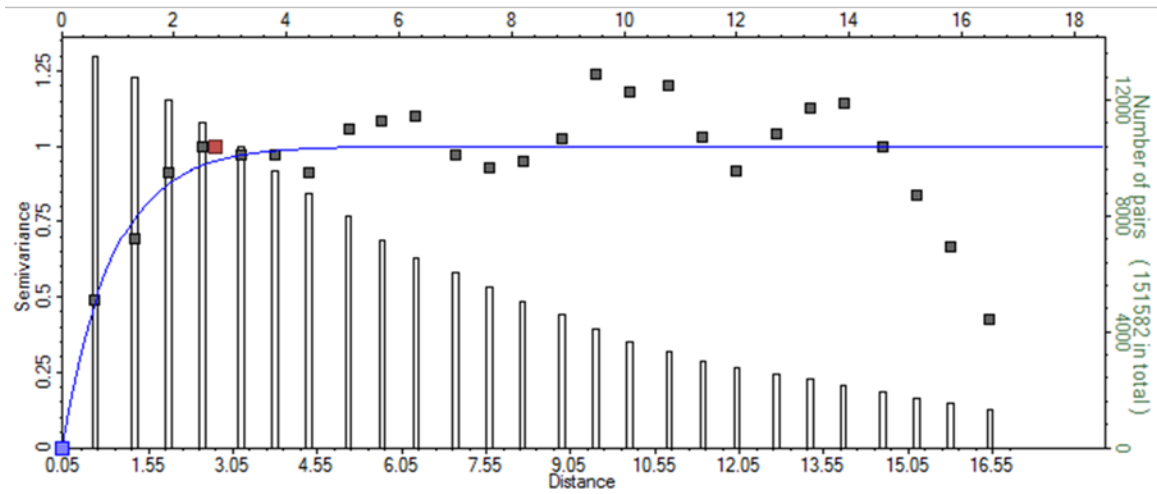


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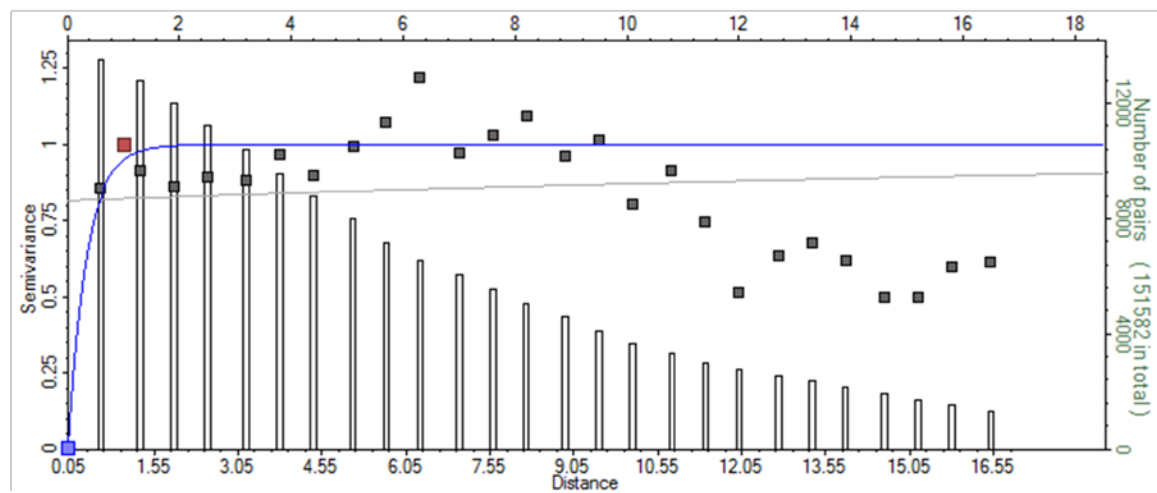


## Zone 16

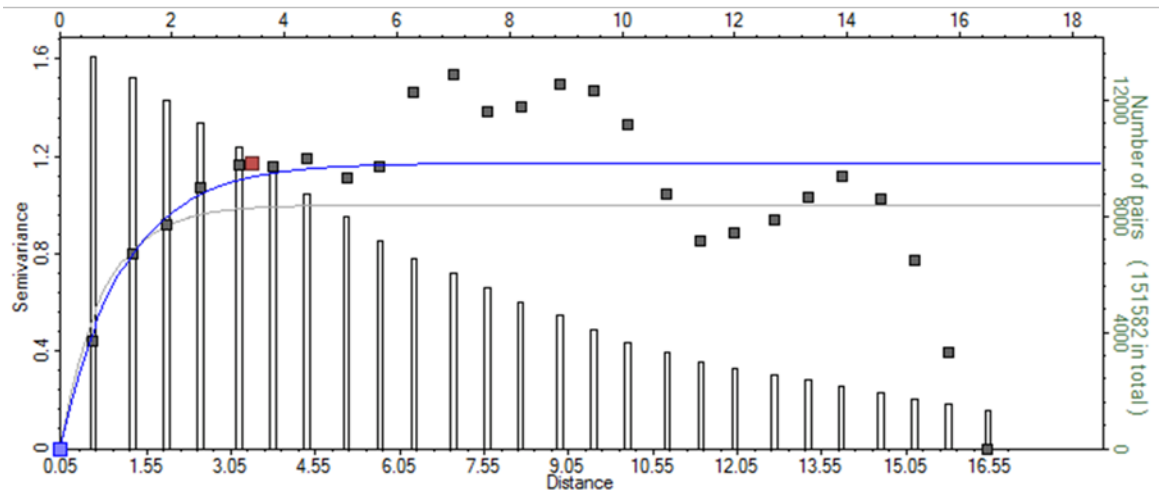
Laminated Sand



Bioturbated Sand



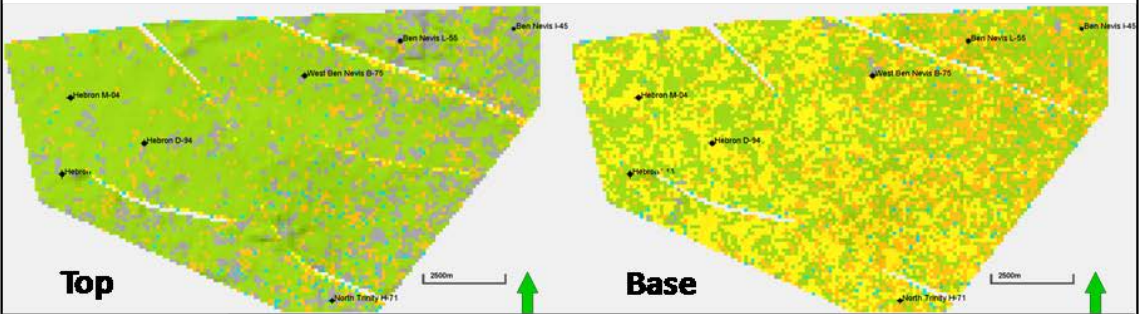
# Calcite



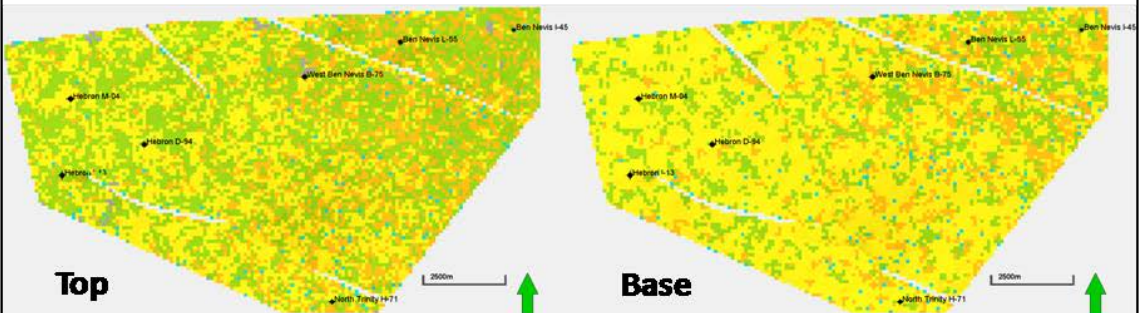
## **Appendix D**

### **Facies Distribution by Zone for the Hebron Asset Reservoir Model**

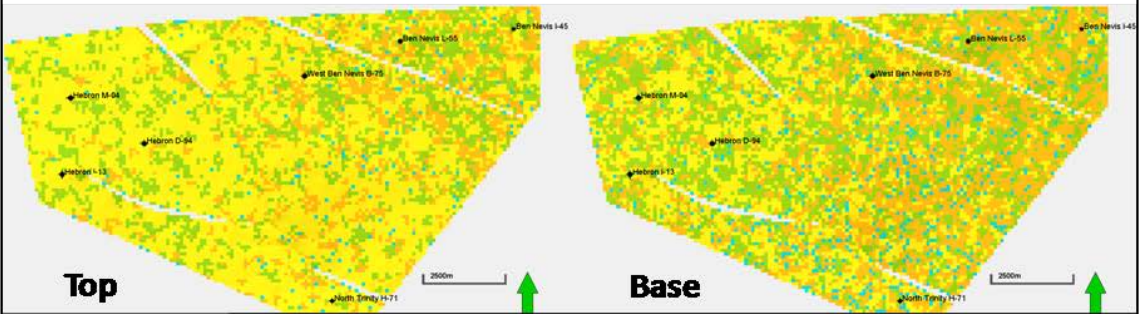
## Zone 1



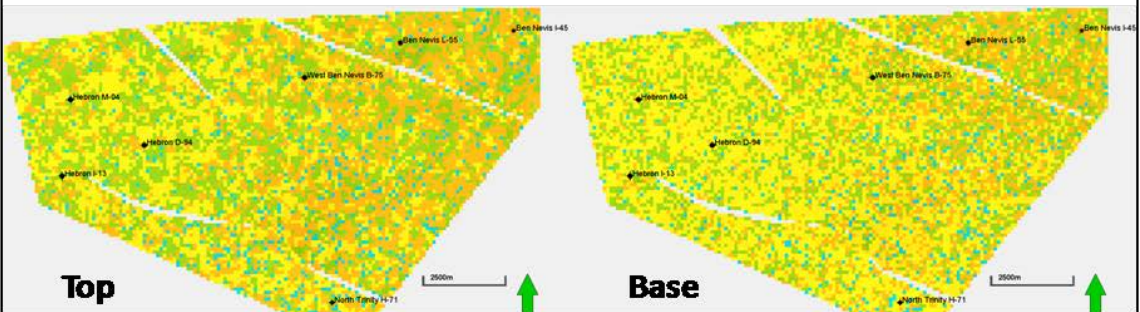
## Zone 2



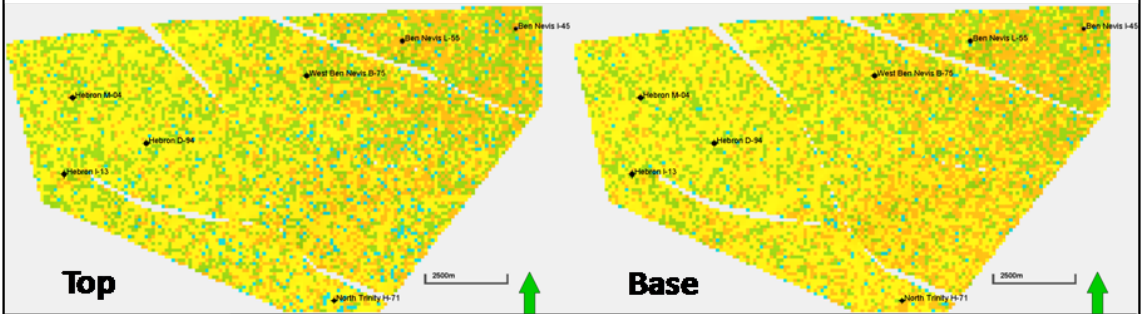
## Zone 3



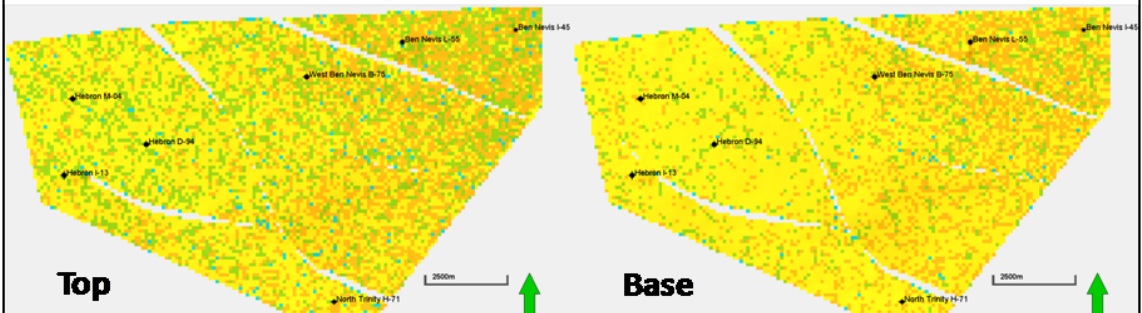
## Zone 4



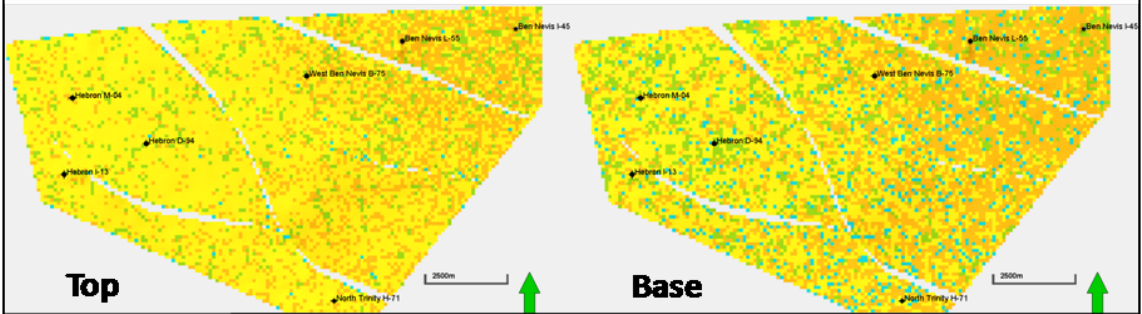
## Zone 5



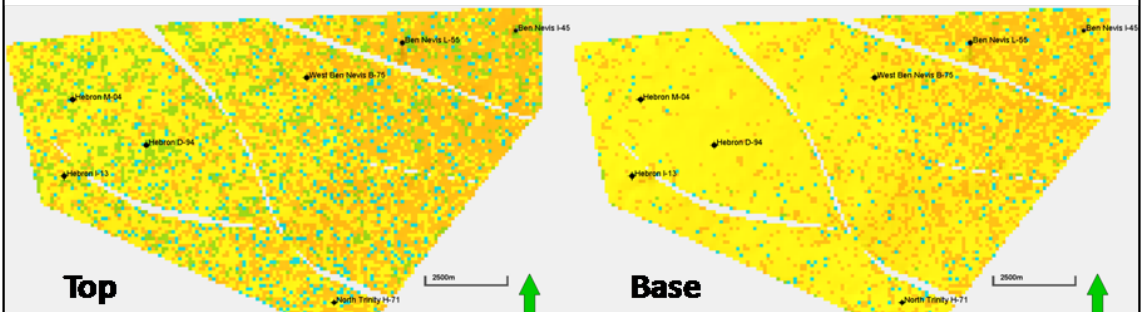
## Zone 6



## Zone 7

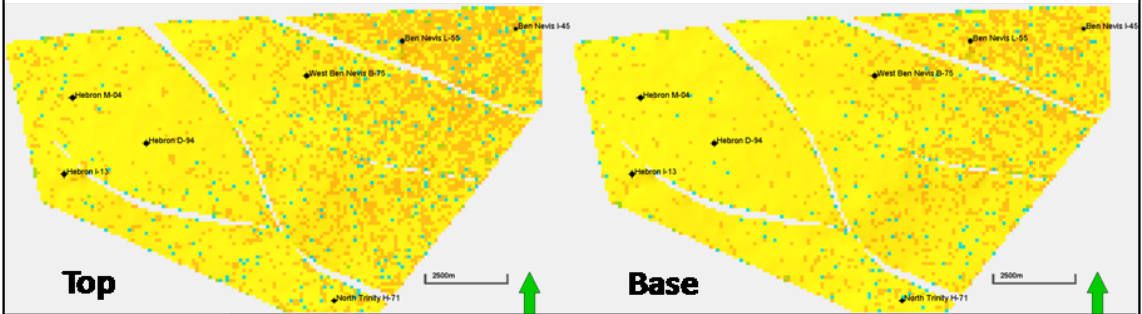


## Zone 8

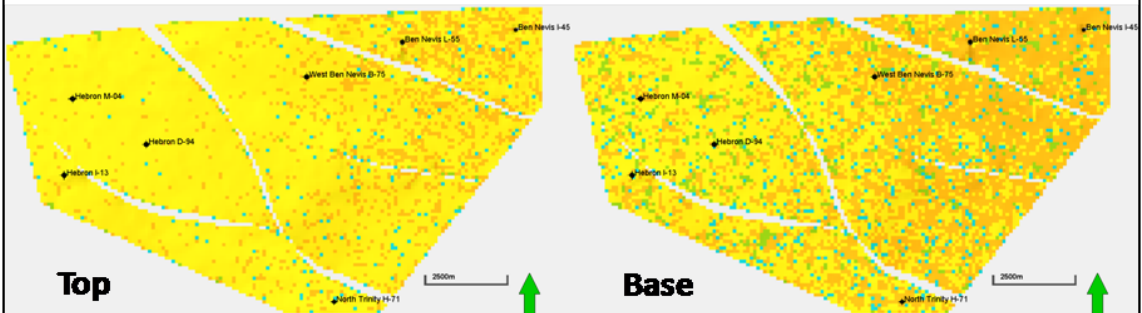




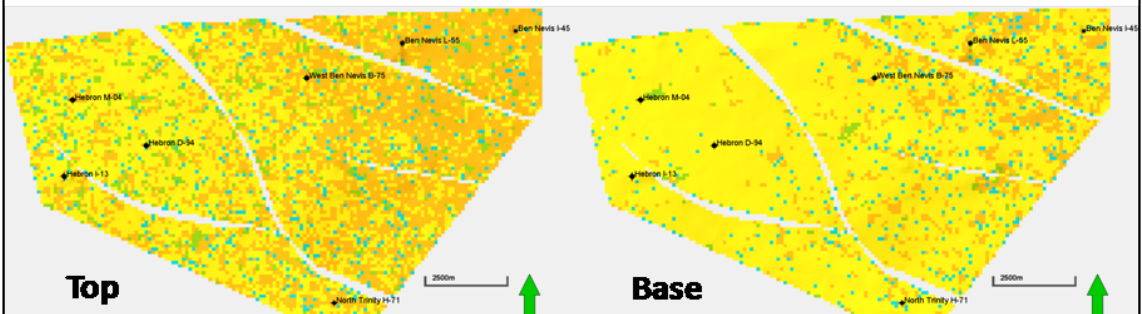
## Zone 9



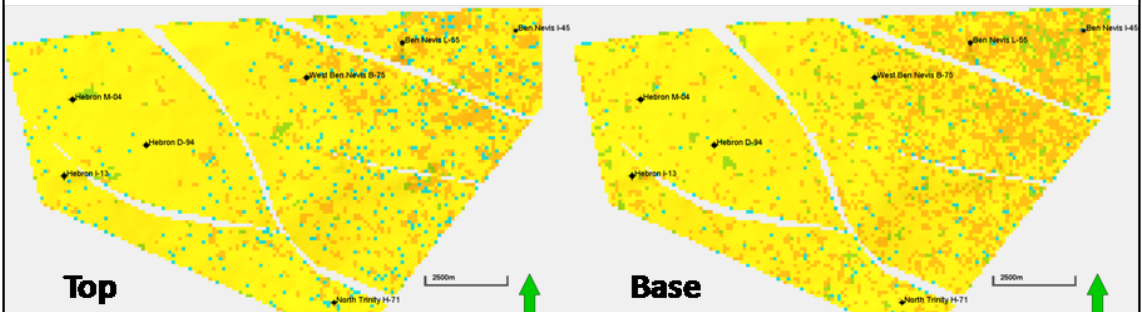
## Zone 10



## Zone 11

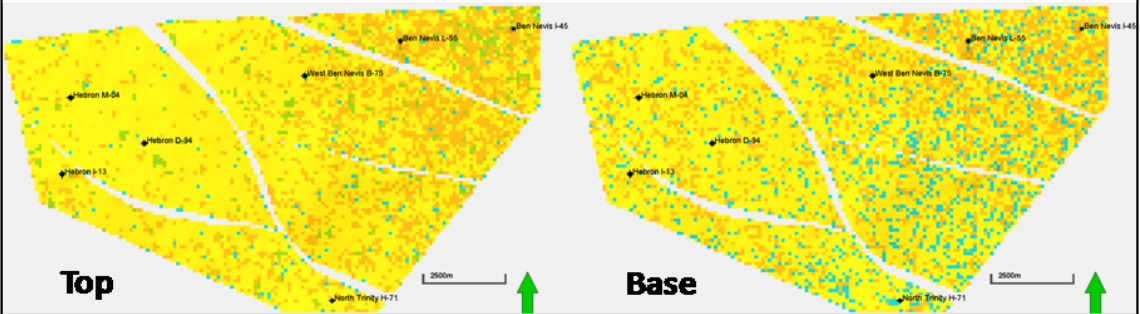


## Zone 12

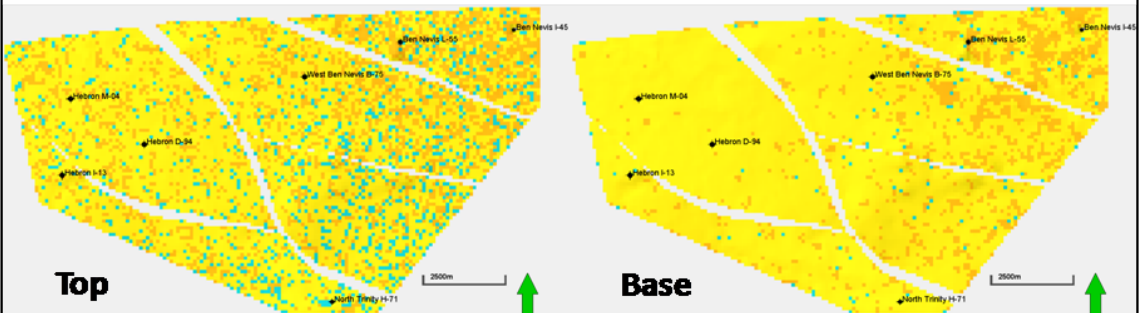




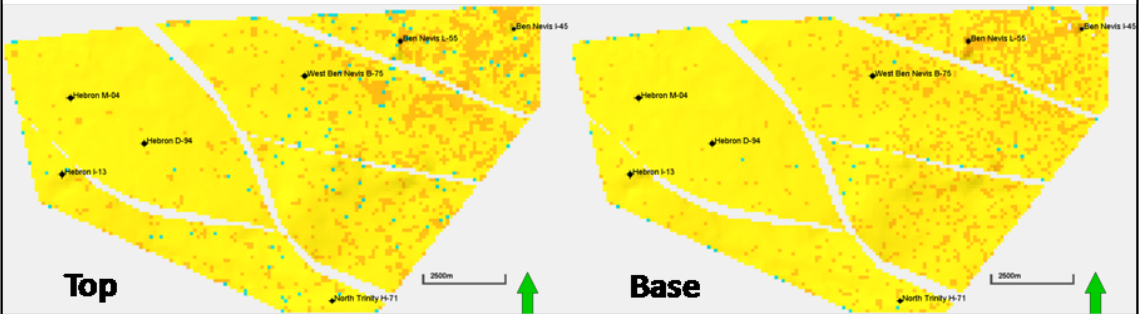
## Zone 13



## Zone 14



## Zone 15



## Zone 16

